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(54) **SYSTEMS AND METHODS FOR DETECTING AND MONITORING ARRHYTHMIAS USING THE PPG**

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(51) **Int. Cl.**

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A61B 5/00	(2006.01)

(52) **U.S. Cl.**

CPC ***A61B 5/14551*** (2013.01); ***A61B 5/726*** (2013.01); ***A61B 5/7282*** (2013.01)

(58) **Field of Classification Search**

USPC 600/324, 481, 483, 485, 500

See application file for complete search history.

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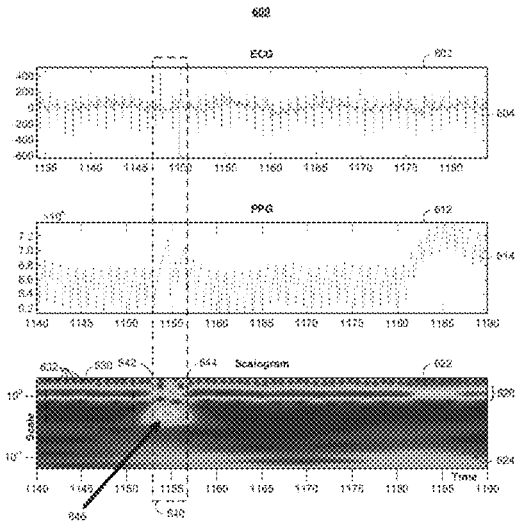
(57) **ABSTRACT**

Systems and methods for detecting and monitoring arrhythmias from a signal are provided. A signal processing system may transform a signal using a wavelet transformation and analyze changes in features of the transformed signal to detect pulse rhythm abnormalities. For example, the system may detect pulse rhythm abnormalities by analyzing energy parameters, morphology changes, and pattern changes in the scalogram of a PPG signal. Further, the system may detect pulse rhythm abnormalities by analyzing both the PPG signal and its corresponding scalogram. Physiological information, such as cardiac arrhythmia, may be derived based on the detected pulse rhythm abnormality.

14 Claims, 14 Drawing Sheets



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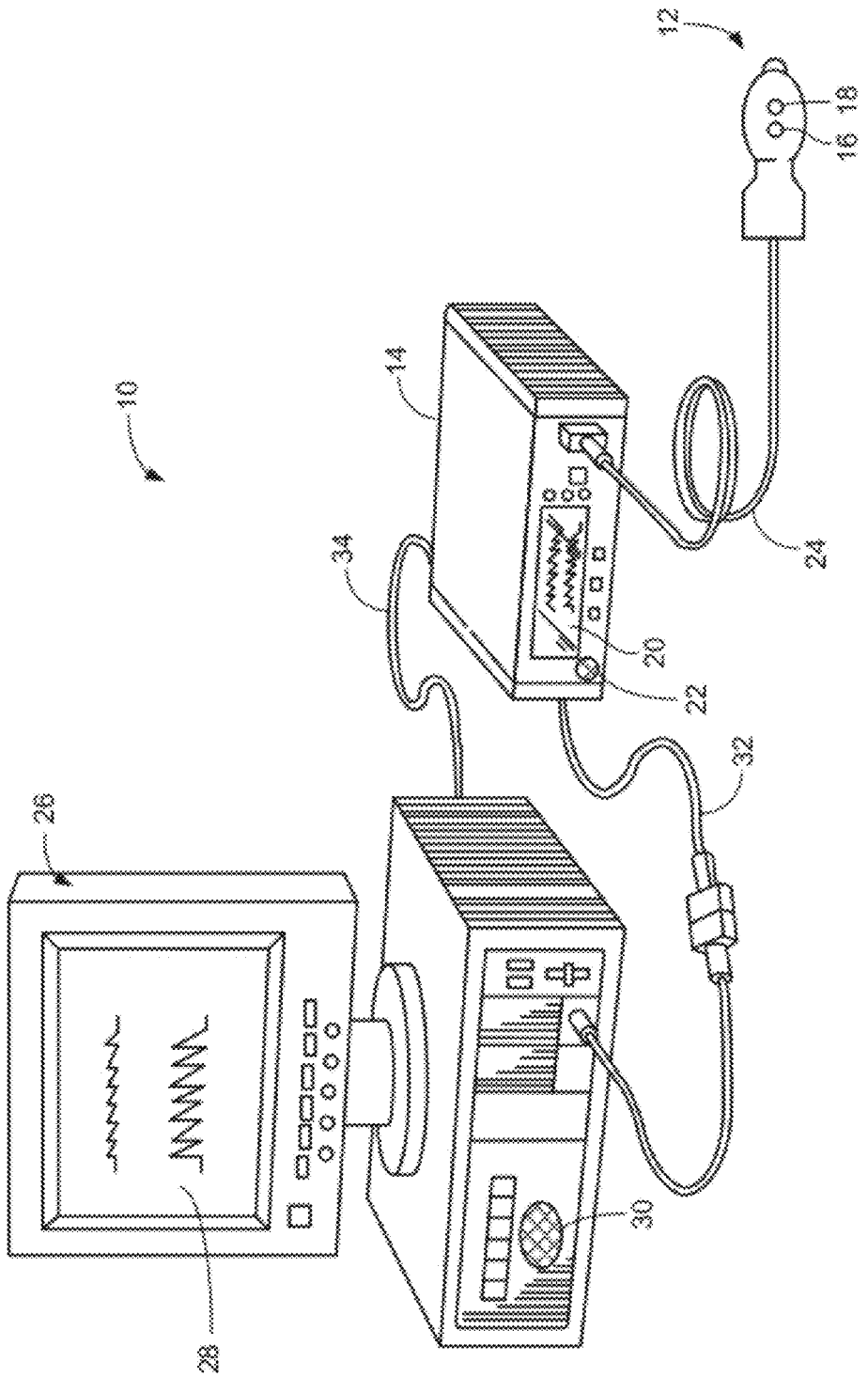
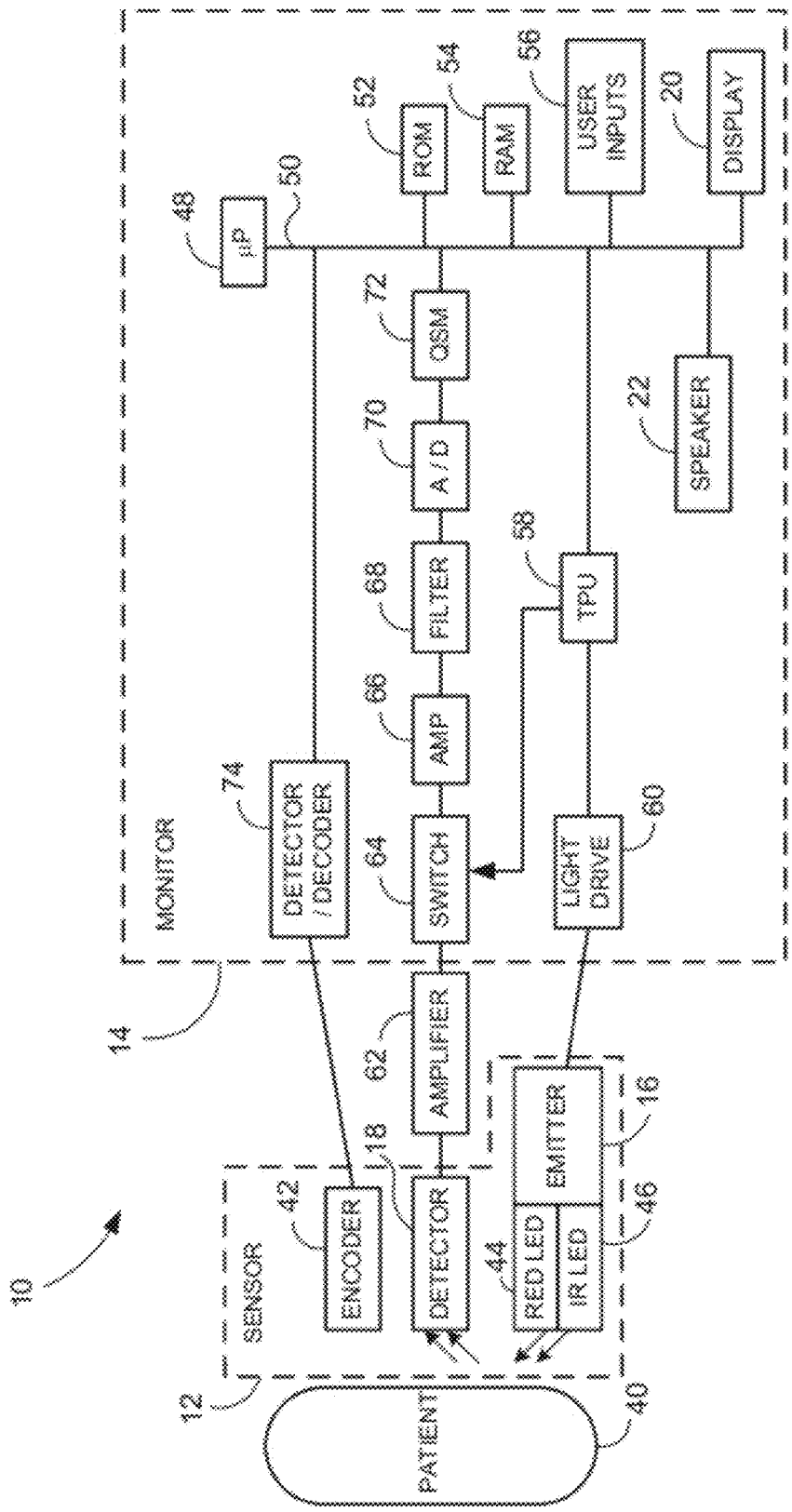


FIG. 1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12
SENSOR
ENCODER
42
DETECTOR
18
RED LED
IR LED
44
46
EMITTER
16
AMPLIFIER
62
14
MONITOR
DETECTOR / DECODER
74
SWITCH
64
AMP
66
FILTER
68
A / D
70
QSM
72
μP
48
50
ROM
52
RAM
54
USER INPUTS
56
DISPLAY
20
SPEAKER
22
TPU
58
LIGHT DRIVE
60
PATIENT
40

FIG. 2

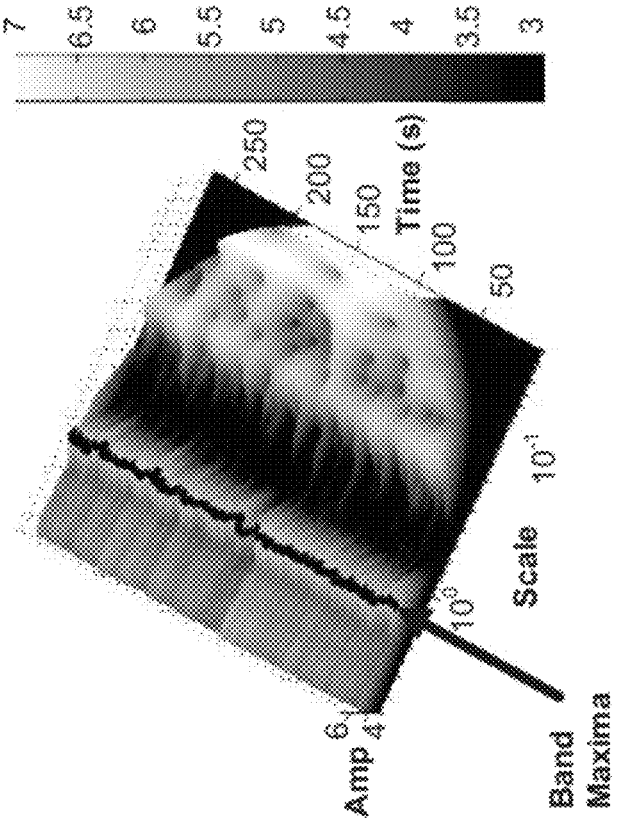

7
6.5
6
5.5
5
4.5
4
3.5
3
250
200
150
100
50
Time (s)
Scale
10^{0}
10^{-1}
Amp
6
4
Band
Maxima

FIG. 3(b)

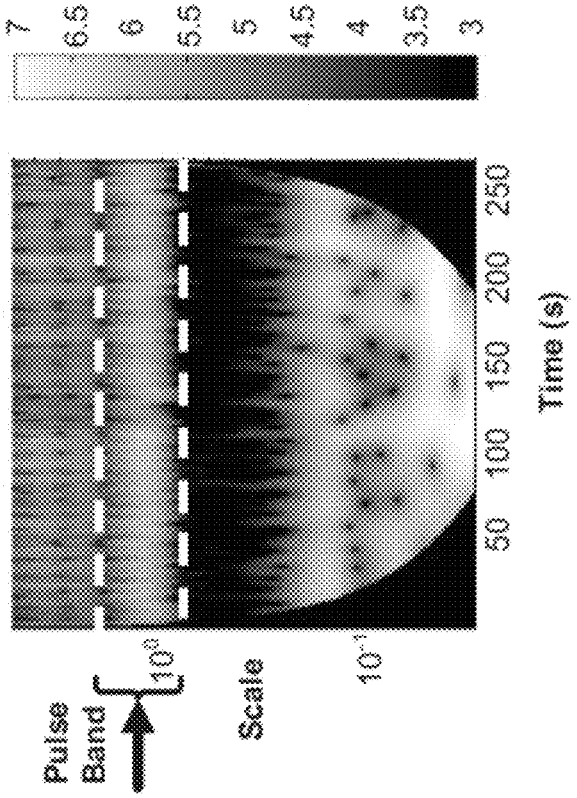

7
6.5
6
5.5
5
4.5
4
3.5
3
50
100
150
200
250
Time (s)
Scale
10^{0}
10^{-1}
Pulse
Band

FIG. 3(a)

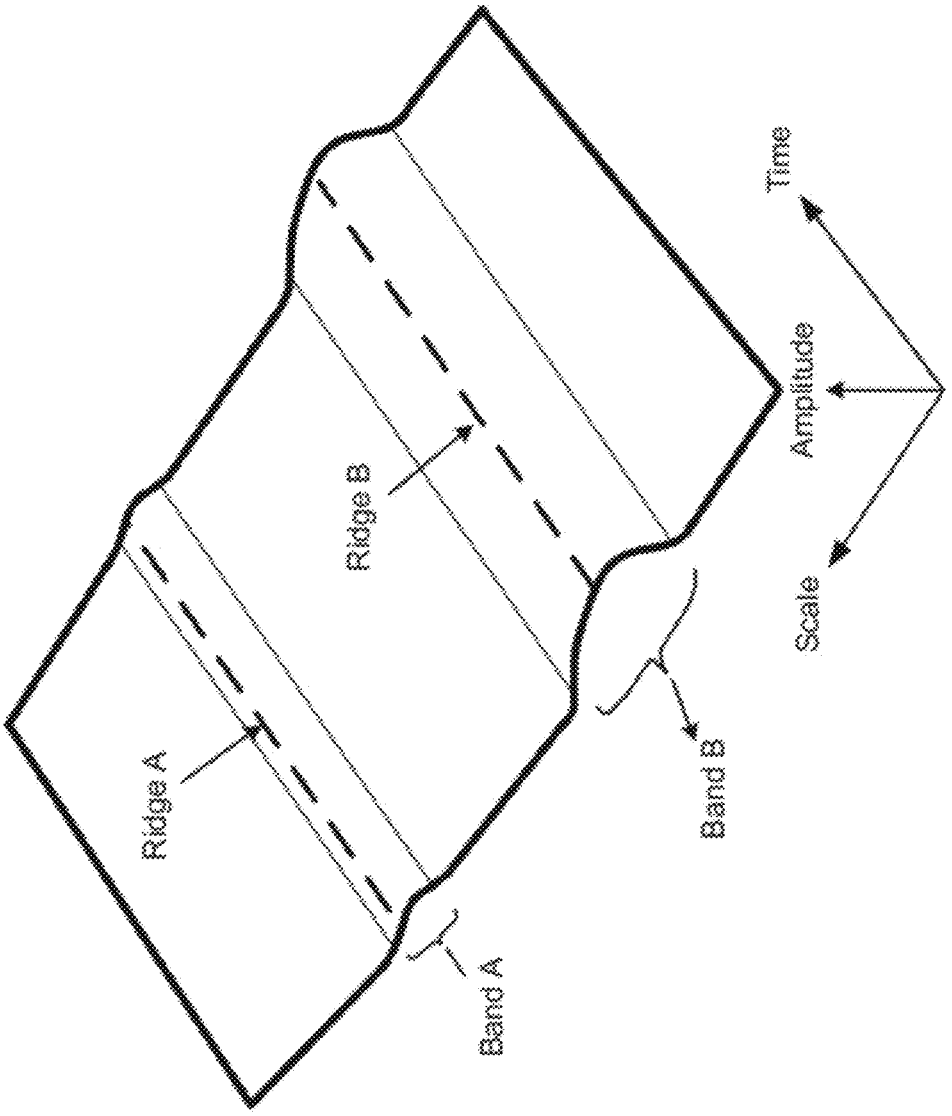


FIG. 3(c)

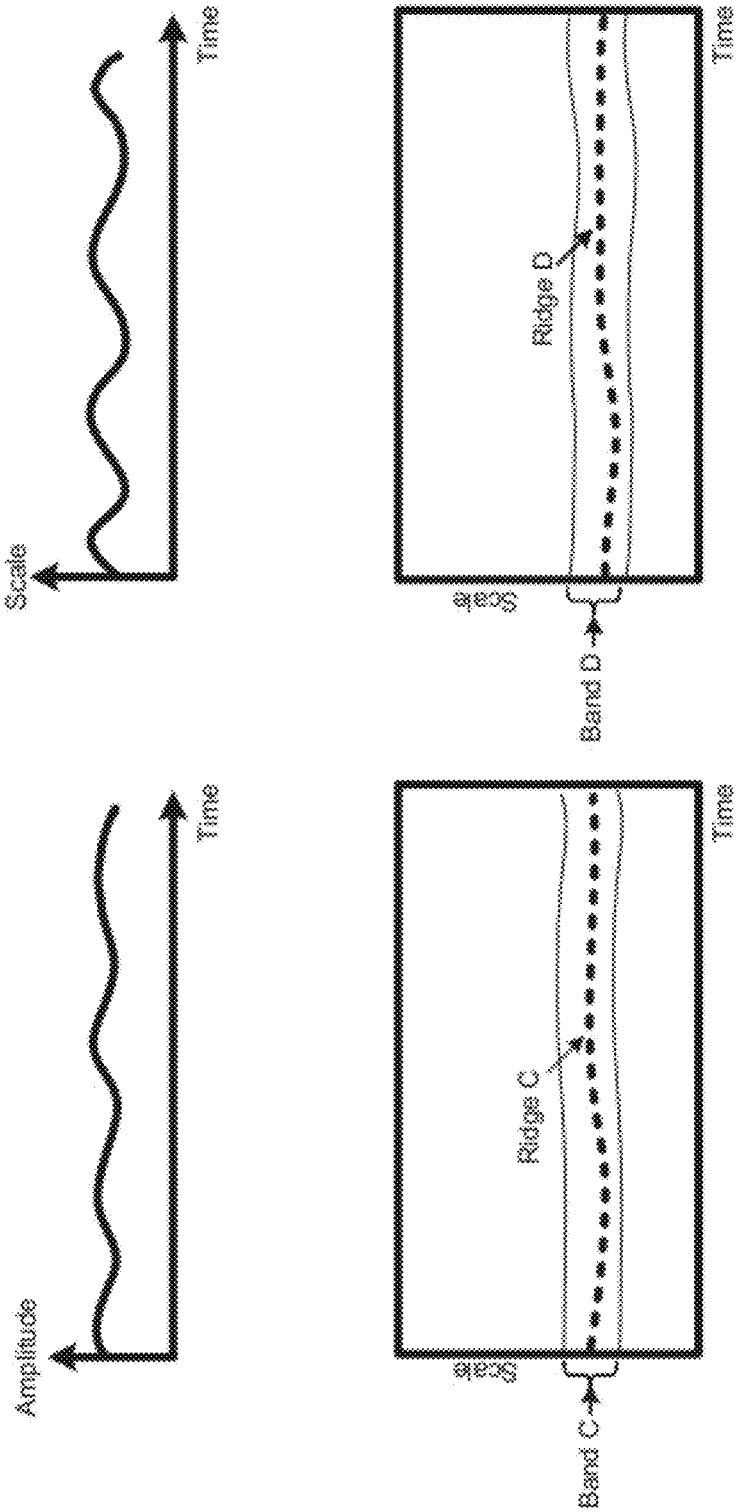

Time
Scale
Ridge D
Time
Scale
Band D
Time
Amplitude
Ridge C
Time
Scale
Band C

FIG. 3(d)

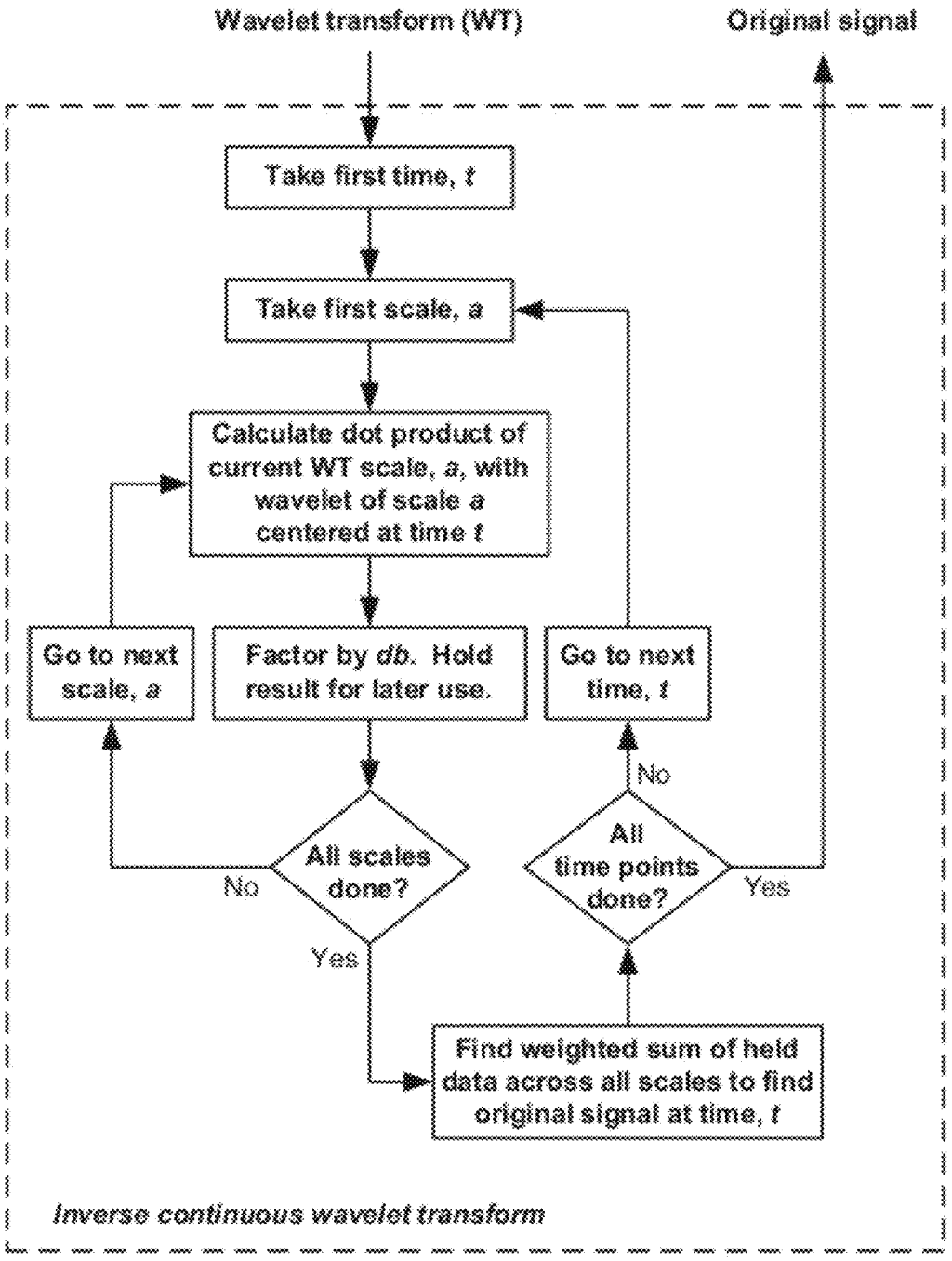

Wavelet transform (WT)
Original signal
Take first time, t
Take first scale, a
Calculate dot product of current WT scale, a, with wavelet of scale a centered at time t
Go to next scale, a
Factor by db. Hold result for later use.
Go to next time, t
No
All scales done?
No
Yes
All time points done?
Yes
Find weighted sum of held data across all scales to find original signal at time, t
Inverse continuous wavelet transform

FIG. 3(e)

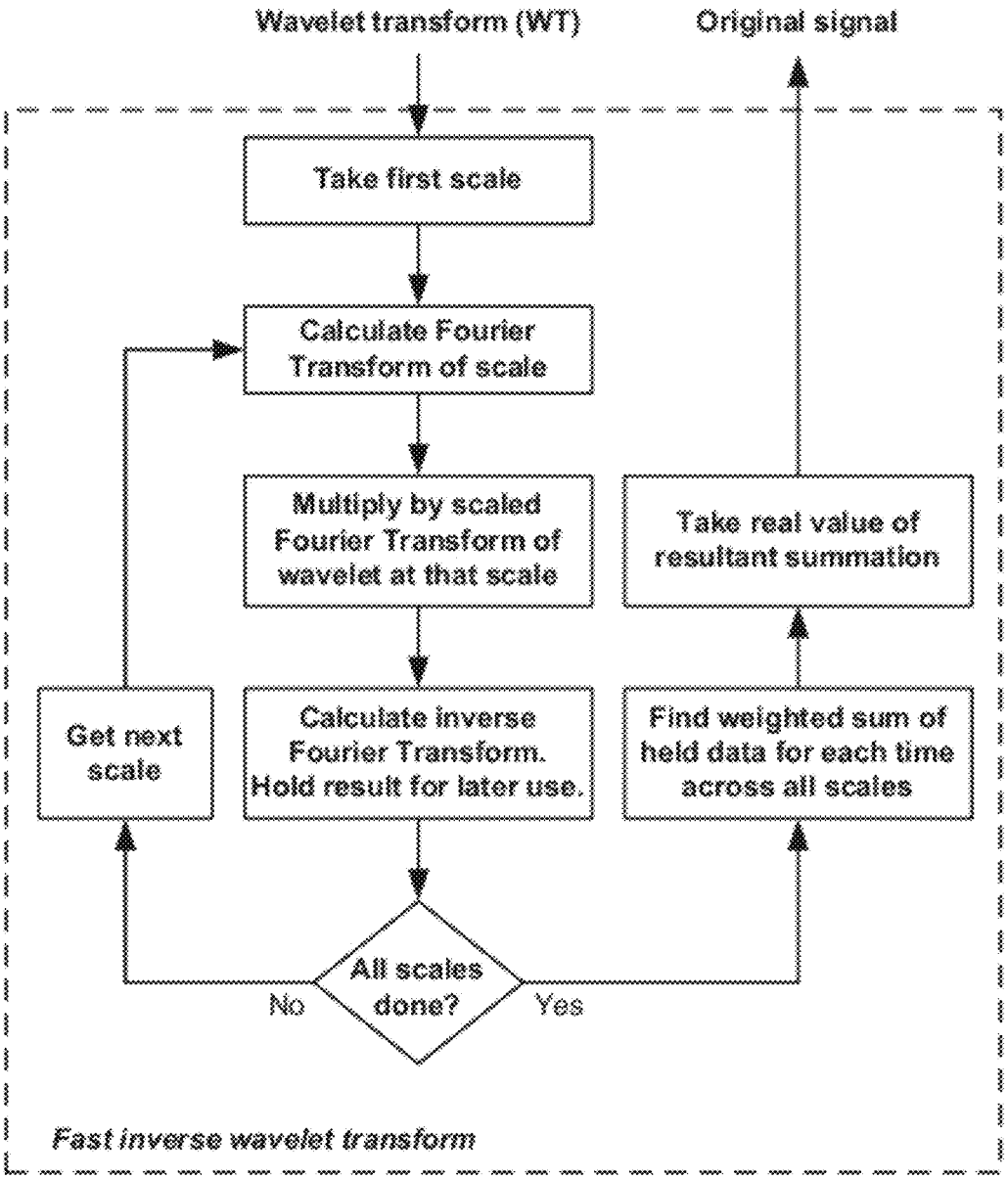

Wavelet transform (WT)
Original signal
Take first scale
Calculate Fourier Transform of scale
Multiply by scaled Fourier Transform of wavelet at that scale
Calculate inverse Fourier Transform. Hold result for later use.
Get next scale
All scales done?
No
Yes
Find weighted sum of held data for each time across all scales
Take real value of resultant summation
Fast inverse wavelet transform

FIG. 3(f)

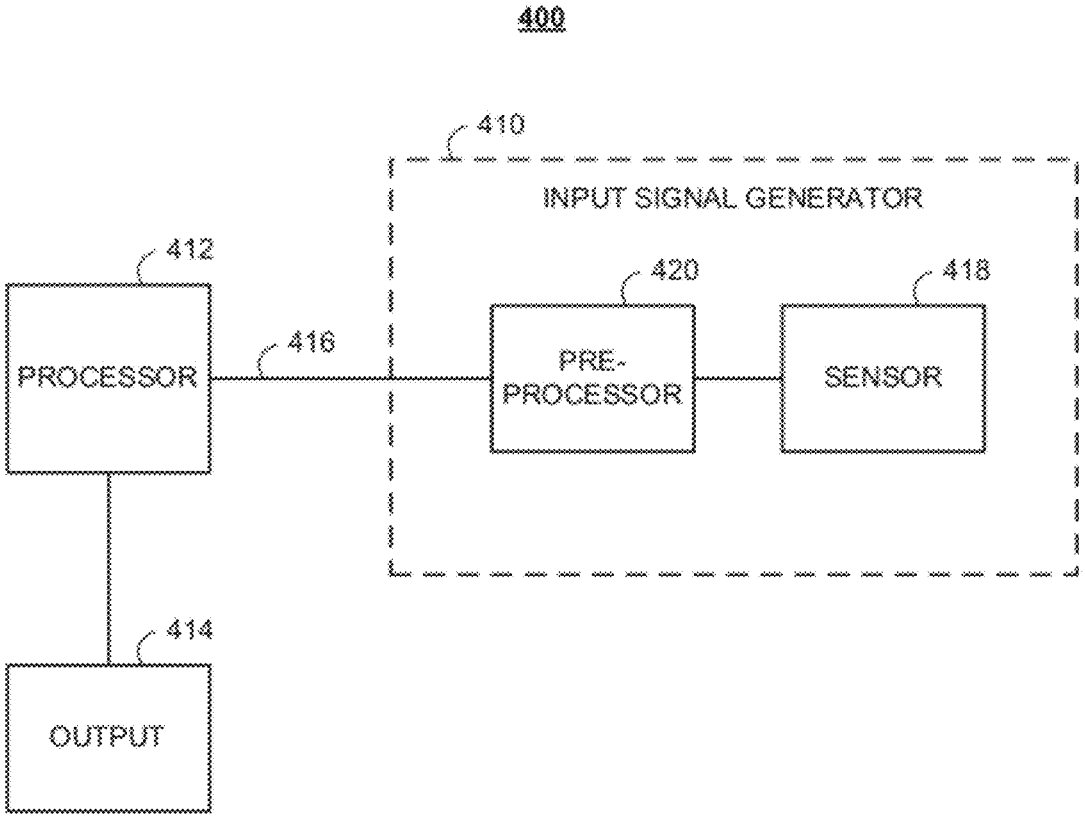

400
410
INPUT SIGNAL GENERATOR
412
PROCESSOR
416
420
PRE-
PROCESSOR
418
SENSOR
414
OUTPUT

FIG. 4

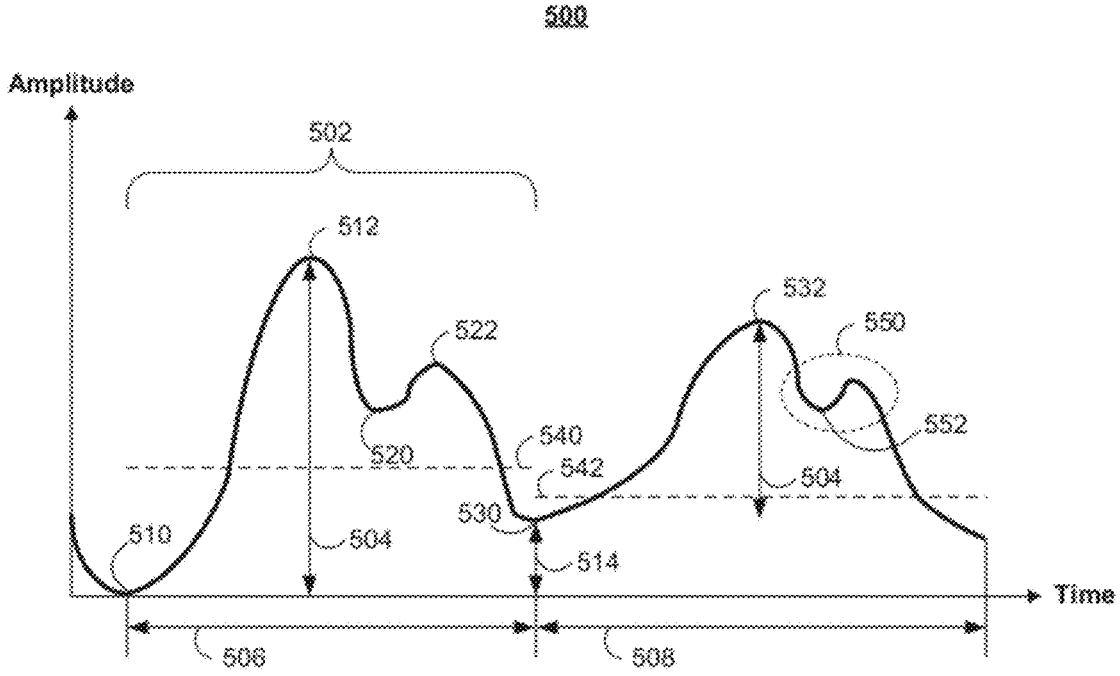

500
Amplitude
502
512
522
532
550
552
520
540
542
504
530
510
504
514
Time
506
506

FIG. 5

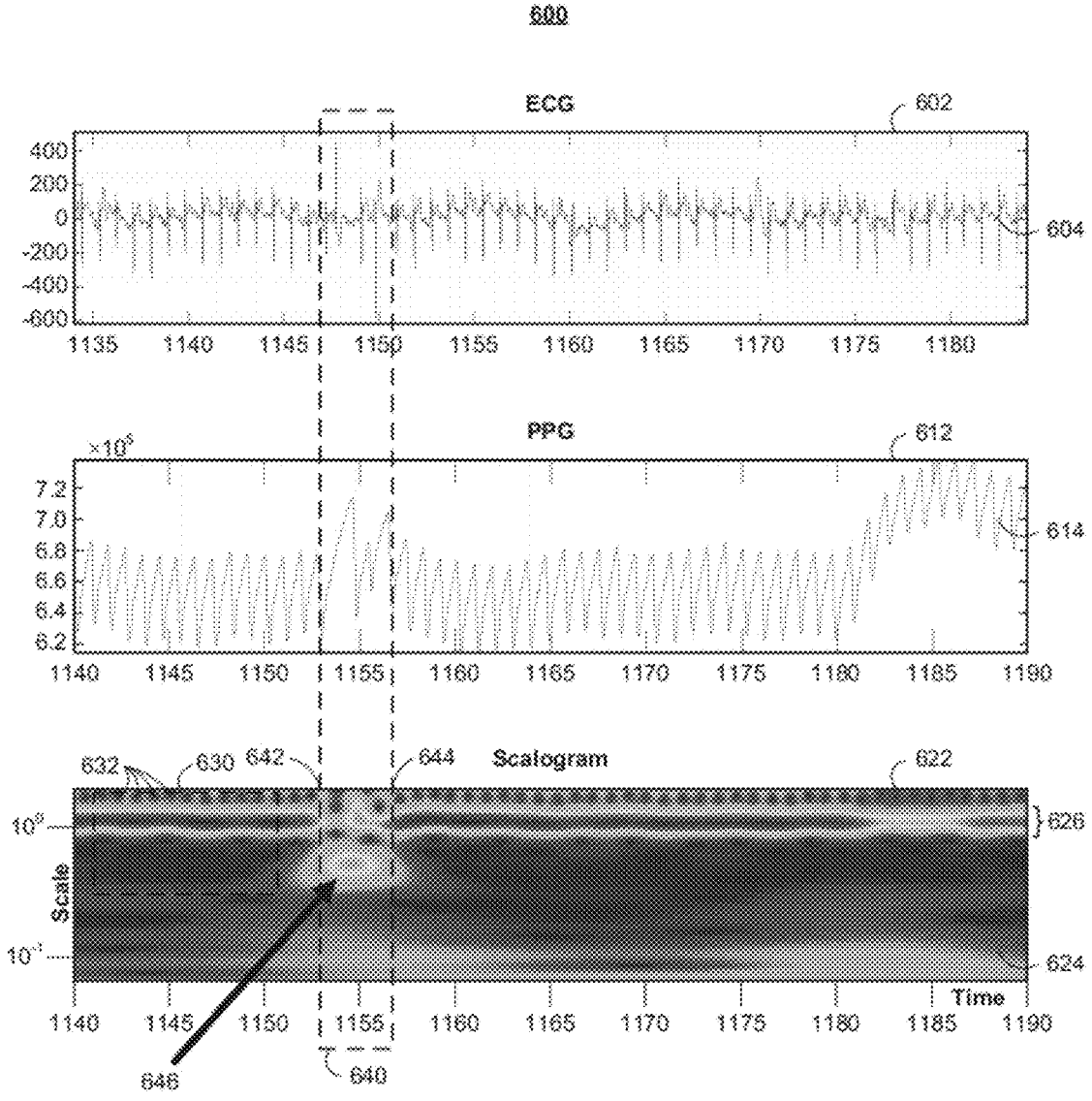

600
ECG
602
400
200
0
-200
-400
-600
604
1135 1140 1145 1150 1155 1160 1165 1170 1175 1180
PPG
612
×10^5
7.2
7.0
6.8
6.6
6.4
6.2
614
1140 1145 1150 1155 1160 1165 1170 1175 1180 1185 1190
632
630
642
644
Scalogram
622
10^0
626
Scale
10^-1
624
Time
1140 1145 1150 1155 1160 1165 1170 1175 1180 1185 1190
646
640

FIG. 6

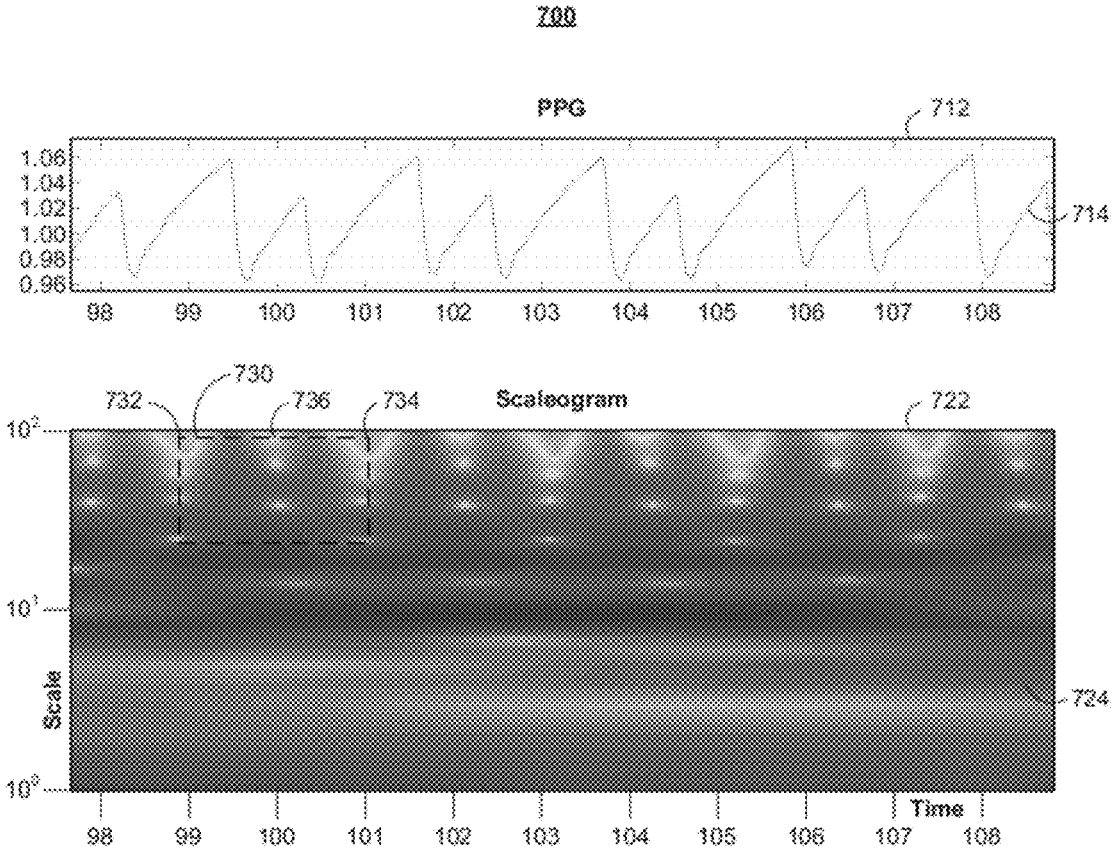

700
PPG
712
1.06
1.04
1.02
1.00
0.98
0.96
714
98
99
100
101
102
103
104
105
106
107
108
730
732
736
734
Scaleogram
722
10^2
10^1
10^0
Scale
724
Time
98
99
100
101
102
103
104
105
106
107
108

FIG. 7

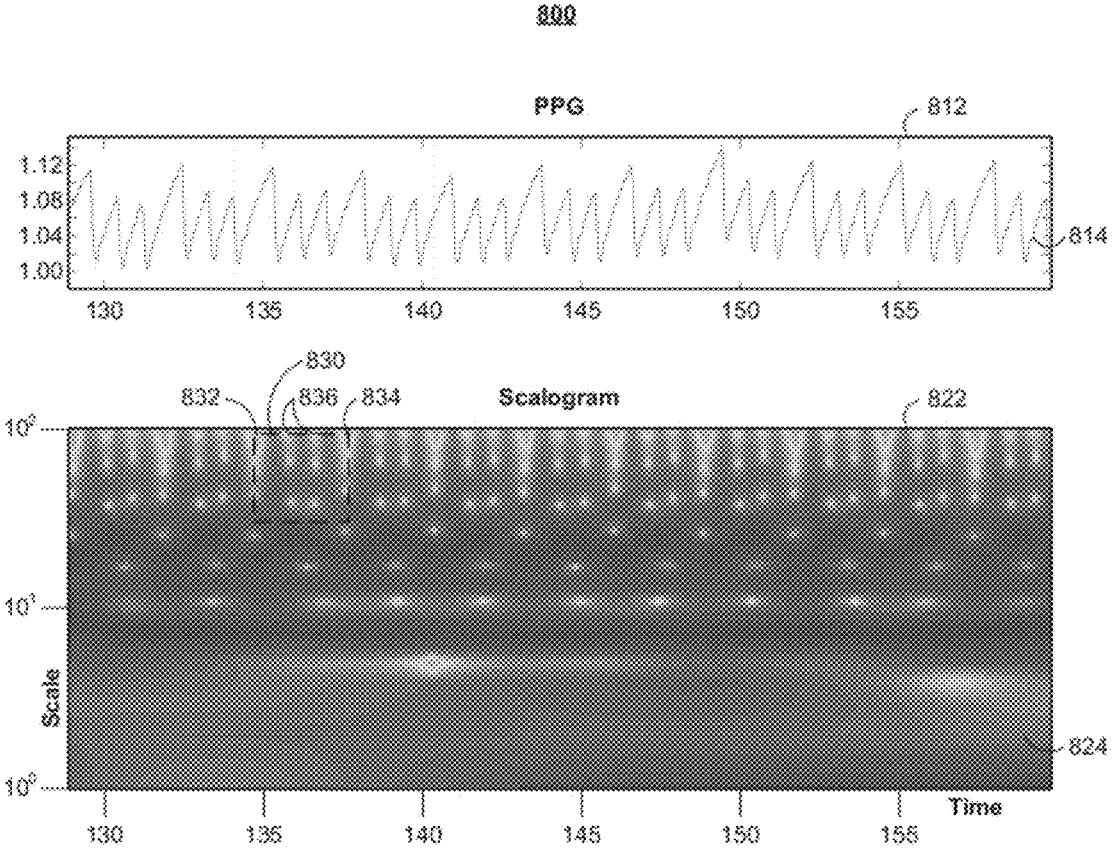
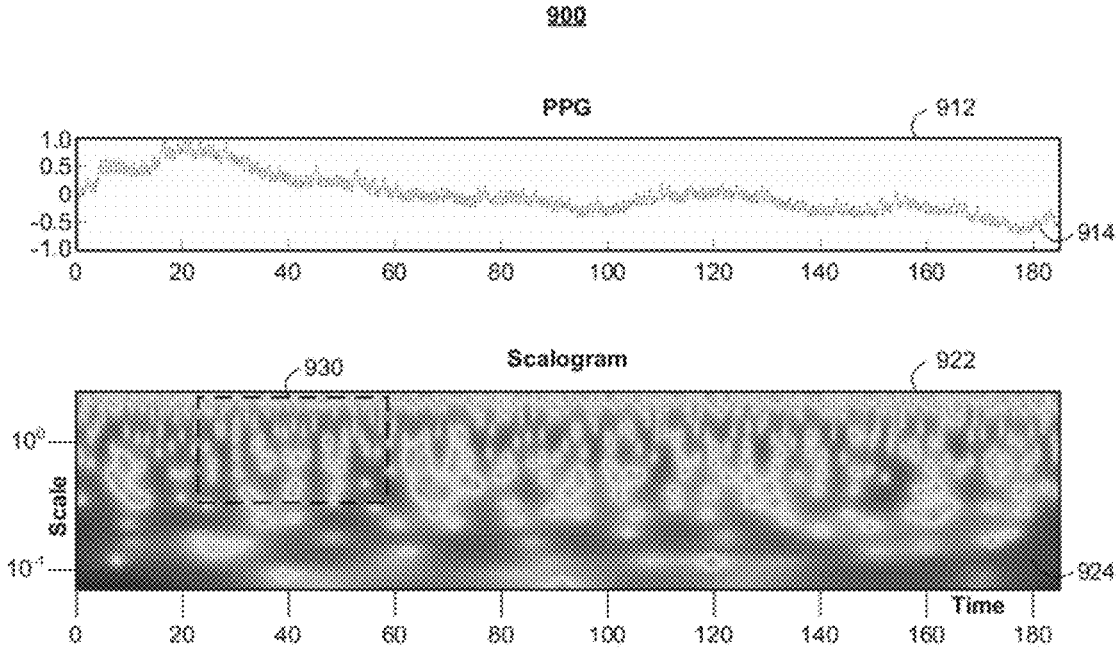

800
PPG
812
1.12
1.08
1.04
1.00
814
130
135
140
145
150
155
830
832
836
834
Scalogram
822
10^2
10^1
10^0
Scale
824
Time
130
135
140
145
150
155

FIG. 8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PPG
912
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0.5
0
-0.5
-1.0
914
0
20
40
60
80
100
120
140
160
180
930
Scalogram
922
Scale
10^{0}
10^{-1}
924
Time

FIG. 9

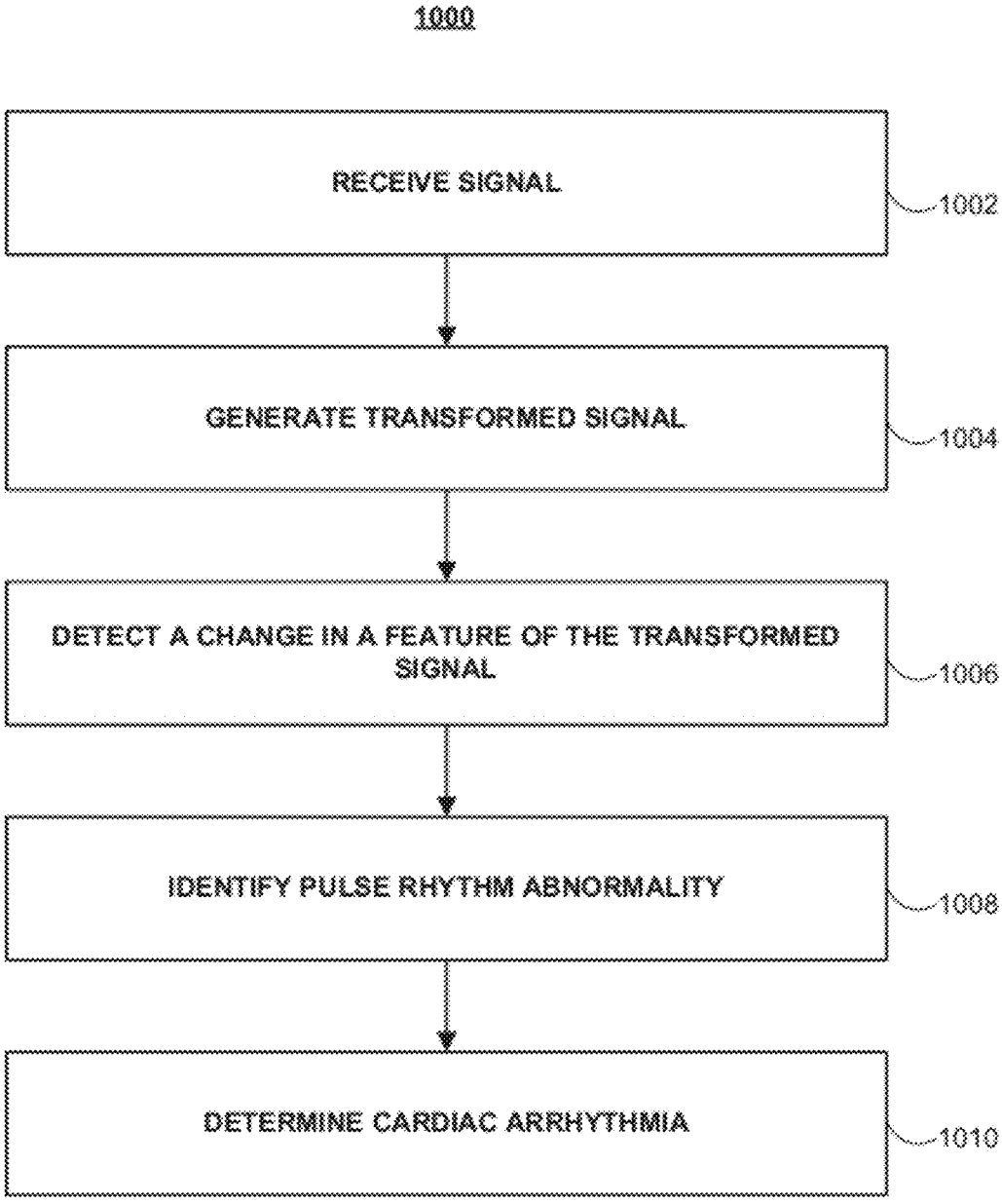
1000
RECEIVE SIGNAL
1002
GENERATE TRANSFORMED SIGNAL
1004
DETECT A CHANGE IN A FEATURE OF THE TRANSFORMED SIGNAL
1006
IDENTIFY PULSE RHYTHM ABNORMALITY
1008
DETERMINE CARDIAC ARRHYTHMIA
1010

FIG. 10

SYSTEMS AND METHODS FOR DETECTING AND MONITORING ARRHYTHMIAS USING THE PPG

SUMMARY OF THE DISCLOSURE

The present disclosure relates to signal processing and, more particularly, the present disclosure relates to identifying heartbeat irregularities from a transformation of a photoplethysmograph (PPG) signal, for example from a wavelet transformation.

A pulse oximeter monitors oxygen saturation and heart rate. Current pulse oximeters are able to detect pulse rate and are therefore able to identify bradycardia (i.e., slow heart rates) and tachycardia (i.e., fast heart rates). However, current pulse oximeters are unable to identify other arrhythmia types (e.g., atrial fibrillation, ventricular fibrillation, ectopic beats, etc.).

The present disclosure describes systems and methods for detecting and monitoring arrhythmia by using a transformation (such as a wavelet transformation) of a received PPG signal. Detection of arrhythmia is important for several reasons. These include identifying potentially serious cardiovascular problems, identifying a change in the severity of existing problems, and keeping arrhythmias from interfering with physiological measurements. The disclosed methods and systems have particular use when an electrocardiograph (ECG) is not connected to a patient.

In some embodiments of the present disclosure, a method for determining cardiac arrhythmia in a subject may include receiving a PPG signal from a sensing device attached to a subject, generating a transformed signal based at least in part on a transformation of the PPG signal, and detecting a change in a feature of the transformed signal. The detected change may then be used to identify one or more pulse rhythm abnormalities, which may in turn be used to determine cardiac arrhythmia in the subject.

In some embodiments of the present disclosure, a system for determining cardiac arrhythmia in a subject may include a signal input and electronic processing equipment. The signal input may be configured to receive a PPG signal of a subject from a sensing device. The electronic processing equipment may be configured to receive the PPG signal and generate a scalogram based at least in part on a wavelet transformation of the photoplethysmograph signal. The electronic processing equipment may then determine an energy distribution of the scalogram for a time interval and compare it against a reference energy distribution to detect a change in the energy distribution of the pulse band region, the region of scales greater than the pulse band region, the region of scales lower than the pulse band region, any other suitable feature, or any combination thereof. In some embodiments, the detected change may be used to identify a pulse rhythm abnormality and determine cardiac arrhythmia in the subject.

BRIEF DESCRIPTION OF THE DRAWINGS

The above and other features of the present disclosure, its nature and various advantages will be more apparent upon consideration of the following detailed description, taken in conjunction with the accompanying drawings in which:

FIG. **1** shows an illustrative pulse oximetry system in accordance with an embodiment;

FIG. **2** is a block diagram of the illustrative pulse oximetry system of FIG. **1** coupled to a patient in accordance with an embodiment;

FIGS. **3**(*a*) and **3**(*b*) show illustrative views of a scalogram derived from a PPG signal in accordance with an embodiment;

FIG. **3**(*c*) shows an illustrative scalogram derived from a signal containing two pertinent components in accordance with an embodiment;

FIG. **3**(*d*) shows an illustrative schematic of signals associated with a ridge in FIG. **3**(*c*) and illustrative schematics of a further wavelet decomposition of these newly derived signals in accordance with an embodiment;

FIGS. **3**(*e*) and **3**(*f*) are flow charts of illustrative steps involved in performing an inverse continuous wavelet transform in accordance with embodiments;

FIG. **4** is a block diagram of an illustrative continuous wavelet processing system in accordance with some embodiments;

FIG. **5** shows signal characteristics of an illustrative PPG signal in accordance with some embodiments;

FIG. **6** shows an ECG signal, a PPG signal, and a corresponding scalogram of a PPG signal in accordance with some embodiments;

FIG. **7** shows another PPG signal and a corresponding scalogram of the PPG signal in accordance with some embodiments;

FIG. **8** shows another PPG signal and a corresponding scalogram of the PPG signal in accordance with some embodiments;

FIG. **9** shows another PPG signal and a corresponding scalogram of the PPG signal in accordance with some embodiments; and

FIG. **10** is a flow chart of illustrative steps involved in determining cardiac arrhythmia in accordance with some embodiments.

DETAILED DESCRIPTION

An oximeter is a medical device that is used to determine the oxygen saturation of the blood. One common type of oximeter is a pulse oximeter, which may indirectly measure the oxygen saturation of a patient's blood (as opposed to measuring oxygen saturation directly by analyzing a blood sample taken from the patient) and changes in blood volume in the skin. Ancillary to the blood oxygen saturation measurement, pulse oximeters may also be used to measure the pulse rate of the patient. Pulse oximeters typically measure and display various blood flow characteristics including, but not limited to, the oxygen saturation of hemoglobin in arterial blood.

An oximeter may include a light sensor that is placed at a site on a patient, typically a fingertip, toe, forehead or earlobe, or in the case of a neonate, across a foot. The oximeter passes light using a light source through blood perfused tissue and photoelectrically senses the absorption of light in the tissue. For example, the oximeter may measure the intensity of light that is received at the light sensor as a function of time. A signal representing light intensity versus time or a mathematical manipulation of this signal (e.g., a scaled version thereof, a log taken thereof, a scaled version of a log taken thereof, etc.) may be referred to as the photoplethysmograph (PPG) signal. In addition, the term "PPG signal," as used herein, may also refer to an absorption signal (i.e., representing the amount of light absorbed by the tissue) or any suitable mathematical manipulation thereof. The light intensity or the amount of light absorbed may then be used to calculate the amount of the blood constituent (e.g., oxyhemoglobin) being measured as well as the pulse rate and when each individual pulse occurs.

The light passed through the tissue is selected to be of one or more wavelengths that are absorbed by the blood in an amount representative of the amount of the blood constituent present in the blood. The amount of light passed through the tissue varies in accordance with the changing amount of blood constituent in the tissue and the related light absorption. Red and infrared wavelengths may be used because it has been observed that highly oxygenated blood will absorb relatively less red light and more infrared light than blood with lower oxygen saturation. By comparing the intensities of two wavelengths at different points in the pulse cycle, it is possible to estimate the blood oxygen saturation of hemoglobin in arterial blood.

When the measured blood parameter is the oxygen saturation of hemoglobin, a convenient starting point assumes a saturation calculation based on Lambert-Beer's law. The following notation will be used herein:

$$I(\lambda,t)=I_o(\lambda)\exp(-(s\beta_o(\lambda)+(1-s)\beta_r(\lambda))l(t)) \quad (1)$$

where:
λ=wavelength;
t=time;
I=intensity of light detected;
I_o=intensity of light transmitted;
s=oxygen saturation;
β_o, β_r=empirically derived absorption coefficients; and
l(t)=a combination of concentration and path length from emitter to detector as a function of time.

The traditional approach measures light absorption at two wavelengths (e.g., red and infrared (IR)), and then calculates saturation by solving for the "ratio of ratios" as follows.

1. First, the natural logarithm of (1) is taken ("log" will be used to represent the natural logarithm) for IR and Red

$$\log I=\log I_o-(s\beta_o+(1-s)\beta_r)l \quad (2)$$

2. (2) is then differentiated with respect to time

$$\frac{d\log I}{dt}=-(s\beta_O+(1-s)\beta_r)\frac{dl}{dt} \quad (3)$$

3. Red (3) is divided by IR (3)

$$\frac{\frac{d\log I(\lambda_R)}{dt}}{\frac{d\log I(\lambda_{IR})}{dt}}=\frac{s\beta_O(\lambda_R)+(1-s)\beta_r(\lambda_R)}{s\beta_O(\lambda_{IR})+(1-s)\beta_r(\lambda_{IR})} \quad (4)$$

4. Solving for s

$$s=\frac{\frac{d\log I(\lambda_{IR})}{dt}\beta_r(\lambda_R)-\frac{d\log I(\lambda_R)}{dt}\beta_r(\lambda_{IR})}{\frac{d\log I(\lambda_R)}{dt}(\beta_O(\lambda_{IR})-\beta_r(\lambda_{IR}))-\frac{d\log I(\lambda_{IR})}{dt}(\beta_O(\lambda_R)-\beta_r(\lambda_R))}$$

Note in discrete time

$$\frac{d\log I(\lambda,t)}{dt}\simeq\log I(\lambda,t_2)-\log I(\lambda,t_1)$$

Using log A−log B=log A/B,

$$\frac{d\log I(\lambda,t)}{dt}\simeq\log\left(\frac{I(t_2,\lambda)}{I(t_1,\lambda)}\right)$$

So, (4) can be rewritten as

$$\frac{\frac{d\log I(\lambda_R)}{dt}}{\frac{d\log I(\lambda_{IR})}{dt}}\simeq\frac{\log\left(\frac{I(t_1,\lambda_R)}{I(t_2,\lambda_R)}\right)}{\log\left(\frac{I(t_1,\lambda_{IR})}{I(t_2,\lambda_{IR})}\right)}=R \quad (5)$$

where R represents the "ratio of ratios." Solving (4) for s using (5) gives

$$s=\frac{\beta_r(\lambda_R)-R\beta_r(\lambda_{IR})}{R(\beta_O(\lambda_{IR})-\beta_r(\lambda_{IR}))-\beta_O(\lambda_R)+\beta_r(\lambda_R)}.$$

From (5), R can be calculated using two points (e.g., PPG maximum and minimum), or a family of points. One method using a family of points uses a modified version of (5). Using the relationship

$$\frac{d\log I}{dt}=\frac{\frac{dI}{dt}}{I} \quad (6)$$

now (5) becomes

$$\begin{aligned}\frac{\frac{d\log I(\lambda_R)}{dt}}{\frac{d\log I(\lambda_{IR})}{dt}}&\simeq\frac{\frac{I(t_2,\lambda_R)-I(t_1,\lambda_R)}{I(t_1,\lambda_R)}}{\frac{I(t_2,\lambda_{IR})-I(t_1,\lambda_{IR})}{I(t_1,\lambda_{IR})}}\\&=\frac{[I(t_2,\lambda_R)-I(t_1,\lambda_R)]I(t_1,\lambda_{IR})}{[I(t_2,\lambda_{IR})-I(t_1,\lambda_{IR})]I(t_1,\lambda_R)}\\&=R\end{aligned} \quad (7)$$

which defines a cluster of points whose slope of y versus x will give R where

$$x(t)=[I(t_2,\lambda_{IR})-I(t_1,\lambda_{IR})]I(t_1,\lambda_R)$$

$$y(t)=[I(t_2,\lambda_r)-I(t_1,\lambda_R)]I(t_1,\lambda_{IR})$$

$$y(t)=Rx(t) \quad (8)$$

FIG. **1** is a perspective view of an embodiment of a pulse oximetry system **10**. System **10** may include a sensor **12** and a pulse oximetry monitor **14**. Sensor **12** may include an emitter **16** for emitting light at two or more wavelengths into a patient's tissue. A detector **18** may also be provided in sensor **12** for detecting the light originally from emitter **16** that emanates from the patient's tissue after passing through the tissue.

According to certain embodiments, system **10** includes a plurality of sensors forming a sensor array in lieu of single sensor **12**. Each of the sensors of the sensor array may be a complementary metal oxide semiconductor (CMOS) sensor. Alternatively, each sensor of the array may be charged coupled device (CCD) sensor. In another embodiment, the sensor array may be made up of a combination of CMOS and

CCD sensors. The CCD sensor may comprise a photoactive region and a transmission region for receiving and transmitting data whereas the CMOS sensor may be made up of an integrated circuit having an array of pixel sensors. Each pixel may have a photodetector and an active amplifier.

According to an embodiment, emitter **16** and detector **18** may be on opposite sides of a digit such as a finger or toe, in which case the light that is emanating from the tissue has passed completely through the digit. In an embodiment, emitter **16** and detector **18** may be arranged so that light from emitter **16** penetrates the tissue and is reflected by the tissue into detector **18**, such as a sensor designed to obtain pulse oximetry data from a patient's forehead.

In an embodiment, the sensor or sensor array may be connected to and draw its power from monitor **14** as shown. In another embodiment, the sensor may be wirelessly connected to monitor **14** and include its own battery or similar power supply (not shown). Monitor **14** may be configured to calculate physiological parameters based at least in part on data received from sensor **12** relating to light emission and detection. In an alternative embodiment, the calculations may be performed on the monitoring device itself and the result of the oximetry reading may be passed to monitor **14**. Further, monitor **14** may include a display **20** configured to display the physiological parameters or other information about the system. In the embodiment shown, monitor **14** may also include a speaker **22** to provide an audible sound that may be used in various other embodiments, such as for example, sounding an audible alarm in the event that a patient's physiological parameters are not within a predefined normal range.

In an embodiment, sensor **12**, or the sensor array, may be communicatively coupled to monitor **14** via a cable **24**. However, in other embodiments, a wireless transmission device (not shown) or the like may be used instead of or in addition to cable **24**.

In the illustrated embodiment, pulse oximetry system **10** may also include a multi-parameter patient monitor **26**. The monitor may be cathode ray tube type, a flat panel display (as shown) such as a liquid crystal display (LCD) or a plasma display, or any other type of monitor now known or later developed. Multi-parameter patient monitor **26** may be configured to calculate physiological parameters and to provide a display **28** for information from monitor **14** and from other medical monitoring devices or systems (not shown). For example, multiparameter patient monitor **26** may be configured to display an estimate of a patient's blood oxygen saturation generated by pulse oximetry monitor **14** (referred to as an "SpO_2" measurement), pulse rate information from monitor **14** and blood pressure from a blood pressure monitor (not shown) on display **28**.

Monitor **14** may be communicatively coupled to multi-parameter patient monitor **26** via a cable **32** or **34** that is coupled to a sensor input port or a digital communications port, respectively and/or may communicate wirelessly (not shown). In addition, monitor **14** and/or multi-parameter patient monitor **26** may be coupled to a network to enable the sharing of information with servers or other workstations (not shown). Monitor **14** may be powered by a battery (not shown) or by a conventional power source such as a wall outlet.

FIG. **2** is a block diagram of a pulse oximetry system, such as pulse oximetry system **10** of FIG. **1**, which may be coupled to a patient **40** in accordance with an embodiment. Certain illustrative components of sensor **12** and monitor **14** are illustrated in FIG. **2**. Sensor **12** may include emitter **16**, detector **18**, and encoder **42**. In the embodiment shown, emitter **16** may be configured to emit at least two wavelengths of light (e.g., RED and IR) into a patient's tissue **40**. Hence, emitter **16** may include a RED light emitting light source such as RED light emitting diode (LED) **44** and an IR light emitting light source such as IR LED **46** for emitting light into the patient's tissue **40** at the wavelengths used to calculate the patient's physiological parameters. In one embodiment, the RED wavelength may be between about 600 nm and about 700 nm, and the IR wavelength may be between about 800 nm and about 1000 nm. In embodiments where a sensor array is used in place of single sensor, each sensor may be configured to emit a single wavelength. For example, a first sensor emits only a RED light while a second only emits an IR light.

It will be understood that, as used herein, the term "light" may refer to energy produced by radiative sources and may include one or more of ultrasound, radio, microwave, millimeter wave, infrared, visible, ultraviolet, gamma ray or X-ray electromagnetic radiation. As used herein, light may also include any wavelength within the radio, microwave, infrared, visible, ultraviolet, or X-ray spectra, and that any suitable wavelength of electromagnetic radiation may be appropriate for use with the present techniques. Detector **18** may be chosen to be specifically sensitive to the chosen targeted energy spectrum of the emitter **16**.

In an embodiment, detector **18** may be configured to detect the intensity of light at the RED and IR wavelengths. Alternatively, each sensor in the array may be configured to detect an intensity of a single wavelength. In operation, light may enter detector **18** after passing through the patient's tissue **40**. Detector **18** may convert the intensity of the received light into an electrical signal. The light intensity is directly related to the absorbance and/or reflectance of light in the tissue **40**. That is, when more light at a certain wavelength is absorbed or reflected, less light of that wavelength is received from the tissue by the detector **18**. After converting the received light to an electrical signal, detector **18** may send the signal to monitor **14**, where physiological parameters may be calculated based on the absorption of the RED and IR wavelengths in the patient's tissue **40**.

In an embodiment, encoder **42** may contain information about sensor **12**, such as what type of sensor it is (e.g., whether the sensor is intended for placement on a forehead or digit) and the wavelengths of light emitted by emitter **16**. This information may be used by monitor **14** to select appropriate algorithms, lookup tables and/or calibration coefficients stored in monitor **14** for calculating the patient's physiological parameters.

Encoder **42** may contain information specific to patient **40**, such as, for example, the patient's age, weight, and diagnosis. This information may allow monitor **14** to determine, for example, patient-specific threshold ranges in which the patient's physiological parameter measurements should fall and to enable or disable additional physiological parameter algorithms. Encoder **42** may, for instance, be a coded resistor which stores values corresponding to the type of sensor **12** or the type of each sensor in the sensor array, the wavelengths of light emitted by emitter **16** on each sensor of the sensor array, and/or the patient's characteristics. In another embodiment, encoder **42** may include a memory on which one or more of the following information may be stored for communication to monitor **14**: the type of the sensor **12**; the wavelengths of light emitted by emitter **16**; the particular wavelength each sensor in the sensor array is monitoring; a signal threshold for each sensor in the sensor array; any other suitable information; or any combination thereof.

In an embodiment, signals from detector **18** and encoder **42** may be transmitted to monitor **14**. In the embodiment shown, monitor **14** may include a general-purpose microprocessor **48** connected to an internal bus **50**. Microprocessor **48** may be

adapted to execute software, which may include an operating system and one or more applications, as part of performing the functions described herein. Also connected to bus **50** may be a read-only memory (ROM) **52**, a random access memory (RAM) **54**, user inputs **56**, display **20**, and speaker **22**.

RAM **54** and ROM **52** are illustrated by way of example, and not limitation. Any suitable computer-readable media may be used in the system for data storage. Computer-readable media are capable of storing information that can be interpreted by microprocessor **48**. This information may be data or may take the form of computer-executable instructions, such as software applications, that cause the microprocessor to perform certain functions and/or computer-implemented methods. Depending on the embodiment, such computer-readable media may include computer storage media and communication media. Computer storage media may include volatile and non-volatile, removable and non-removable media implemented in any method or technology for storage of information such as computer-readable instructions, data structures, program modules or other data. Computer storage media may include, but is not limited to, RAM, ROM, EPROM, EEPROM, flash memory or other solid state memory technology, CD-ROM, DVD, or other optical storage, magnetic cassettes, magnetic tape, magnetic disk storage or other magnetic storage devices, or any other medium which can be used to store the desired information and which can be accessed by components of the system.

In the embodiment shown, a time processing unit (TPU) **58** may provide timing control signals to a light drive circuitry **60**, which may control when emitter **16** is illuminated and multiplexed timing for the RED LED **44** and the IR LED **46**. TPU **58** may also control the gating-in of signals from detector **18** through an amplifier **62** and a switching circuit **64**. These signals are sampled at the proper time, depending upon which light source is illuminated. The received signal from detector **18** may be passed through an amplifier **66**, a low pass filter **68**, and an analog-to-digital converter **70**. The digital data may then be stored in a queued serial module (QSM) **72** (or buffer) for later downloading to RAM **54** as QSM **72** fills up. In one embodiment, there may be multiple separate parallel paths having amplifier **66**, filter **68**, and A/D converter **70** for multiple light wavelengths or spectra received.

In an embodiment, microprocessor **48** may determine the patient's physiological parameters, such as SpO_2 and pulse rate, using various algorithms and/or look-up tables based on the value of the received signals and/or data corresponding to the light received by detector **18**. Signals corresponding to information about patient **40**, and particularly about the intensity of light emanating from a patient's tissue over time, may be transmitted from encoder **42** to a decoder **74**. These signals may include, for example, encoded information relating to patient characteristics. Decoder **74** may translate these signals to enable the microprocessor to determine the thresholds based on algorithms or look-up tables stored in ROM **52**. User inputs **56** may be used to enter information about the patient, such as age, weight, height, diagnosis, medications, treatments, and so forth. In an embodiment, display **20** may exhibit a list of values which may generally apply to the patient, such as, for example, age ranges or medication families, which the user may select using user inputs **56**.

The optical signal through the tissue can be degraded by noise, among other sources. One source of noise is ambient light that reaches the light detector. Another source of noise is electromagnetic coupling from other electronic instruments. Movement of the patient also introduces noise and affects the signal. For example, the contact between the detector and the skin, or the emitter and the skin, can be temporarily disrupted when movement causes either to move away from the skin. In addition, because blood is a fluid, it responds differently than the surrounding tissue to inertial effects, thus resulting in momentary changes in volume at the point to which the oximeter probe is attached.

Noise (e.g., from patient movement) can degrade a pulse oximetry signal relied upon by a physician, without the physician's awareness. This is especially true if the monitoring of the patient is remote, the motion is too small to be observed, or the doctor is watching the instrument or other parts of the patient, and not the sensor site. Processing pulse oximetry (i.e., PPG) signals may involve operations that reduce the amount of noise present in the signals or otherwise identify noise components in order to prevent them from affecting measurements of physiological parameters derived from the PPG signals.

It will be understood that the present disclosure is applicable to any suitable signals and that PPG signals are used merely for illustrative purposes. Those skilled in the art will recognize that the present disclosure has wide applicability to other signals including, but not limited to other biosignals (e.g., electrocardiogram, electroencephalogram, electrogastrogram, electromyogram, heart rate signals, pathological sounds, ultrasound, or any other suitable biosignal), dynamic signals, non-destructive testing signals, condition monitoring signals, fluid signals, geophysical signals, astronomical signals, electrical signals, financial signals including financial indices, sound and speech signals, chemical signals, meteorological signals including climate signals, and/or any other suitable signal, and/or any combination thereof.

In certain embodiments, a PPG signal is transformed using a continuous wavelet transform. Information derived from the transform of the PPG signal (i.e., in wavelet space) may be used to provide measurements of one or more physiological parameters.

The continuous wavelet transform of a signal x(t) in accordance with the present disclosure may be defined as

$$T(a,b)=\frac{1}{\sqrt{a}}\int_{-\infty}^{+\infty}x(t)\psi*\left(\frac{t-b}{a}\right)dt \tag{9}$$

where $\psi r^*(t)$ is the complex conjugate of the wavelet function $\psi(t)$, a is the dilation parameter of the wavelet and b is the location parameter of the wavelet. The transform given by equation (9) may be used to construct a representation of a signal on a transform surface. The transform may be regarded as a time-scale representation. Wavelets are composed of a range of frequencies, one of which may be denoted as the characteristic frequency of the wavelet, where the characteristic frequency associated with the wavelet is inversely proportional to the scale a. One example of a characteristic frequency is the dominant frequency. Each scale of a particular wavelet may have a different characteristic frequency. The underlying mathematical detail required for the implementation within a time-scale can be found, for example, in Paul S. Addison, The Illustrated Wavelet Transform Handbook (Taylor & Francis Group 2002), which is hereby incorporated by reference herein in its entirety.

The continuous wavelet transform decomposes a signal using wavelets, which are generally highly localized in time. The continuous wavelet transform may provide a higher resolution relative to discrete transforms, thus providing the ability to garner more information from signals than typical frequency transforms such as Fourier transforms (or any other spectral techniques) or discrete wavelet transforms. Continu-

ous wavelet transforms allow for the use of a range of wavelets with scales spanning the scales of interest of a signal such that small scale signal components correlate well with the smaller scale wavelets and thus manifest at high energies at smaller scales in the transform. Likewise, large scale signal components correlate well with the larger scale wavelets and thus manifest at high energies at larger scales in the transform. Thus, components at different scales may be separated and extracted in the wavelet transform domain. Moreover, the use of a continuous range of wavelets in scale and time position allows for a higher resolution transform than is possible relative to discrete techniques.

In addition, transforms and operations that convert a signal or any other type of data into a spectral (i.e., frequency) domain necessarily create a series of frequency transform values in a two-dimensional coordinate system where the two dimensions may be frequency and, for example, amplitude. For example, any type of Fourier transform would generate such a two-dimensional spectrum. In contrast, wavelet transforms, such as continuous wavelet transforms, are required to be defined in a three-dimensional coordinate system and generate a surface with dimensions of time, scale and, for example, amplitude. Hence, operations performed in a spectral domain cannot be performed in the wavelet domain; instead the wavelet surface must be transformed into a spectrum (i.e., by performing an inverse wavelet transform to convert the wavelet surface into the time domain and then performing a spectral transform from the time domain). Conversely, operations performed in the wavelet domain cannot be performed in the spectral domain; instead a spectrum must first be transformed into a wavelet surface (i.e., by performing an inverse spectral transform to convert the spectral domain into the time domain and then performing a wavelet transform from the time domain). Nor does a cross-section of the three-dimensional wavelet surface along, for example, a particular point in time equate to a frequency spectrum upon which spectral-based techniques may be used. At least because wavelet space includes a time dimension, spectral techniques and wavelet techniques are not interchangeable. It will be understood that converting a system that relies on spectral domain processing to one that relies on wavelet space processing would require significant and fundamental modifications to the system in order to accommodate the wavelet space processing (e.g., to derive a representative energy value for a signal or part of a signal requires integrating twice, across time and scale, in the wavelet domain while, conversely, one integration across frequency is required to derive a representative energy value from a spectral domain). As a further example, to reconstruct a temporal signal requires integrating twice, across time and scale, in the wavelet domain while, conversely, one integration across frequency is required to derive a temporal signal from a spectral domain. It is well known in the art that, in addition to or as an alternative to amplitude, parameters such as energy density, modulus, phase, among others may all be generated using such transforms and that these parameters have distinctly different contexts and meanings when defined in a two-dimensional frequency coordinate system rather than a three-dimensional wavelet coordinate system. For example, the phase of a Fourier system is calculated with respect to a single origin for all frequencies while the phase for a wavelet system is unfolded into two dimensions with respect to a wavelet's location (often in time) and scale.

The energy density function of the wavelet transform, the scalogram, is defined as

$$S(a,b)=|T(a,b)|^2 \tag{10}$$

where '||' is the modulus operator. The scalogram may be resealed for useful purposes. One common resealing is defined as

$$S_R(a,b)=\frac{|T(a,b)|^2}{a} \tag{11}$$

and is useful for defining ridges in wavelet space when, for example, the Morlet wavelet is used. Ridges are defined as the locus of points of local maxima in the plane. Any reasonable definition of a ridge may be employed in the method. Also included as a definition of a ridge herein are paths displaced from the locus of the local maxima. A ridge associated with only the locus of points of local maxima in the plane are labeled a "maxima ridge".

For implementations requiring fast numerical computation, the wavelet transform may be expressed as an approximation using Fourier transforms. Pursuant to the convolution theorem, because the wavelet transform is the cross-correlation of the signal with the wavelet function, the wavelet transform may be approximated in terms of an inverse FFT of the product of the Fourier transform of the signal and the Fourier transform of the wavelet for each required a scale and then multiplying the result by $\sqrt{a}$.

In the discussion of the technology which follows herein, the "scalogram" may be taken to include all suitable forms of resealing including, but not limited to, the original unsealed wavelet representation, linear resealing, any power of the modulus of the wavelet transform, or any other suitable resealing. In addition, for purposes of clarity and conciseness, the term "scalogram" shall be taken to mean the wavelet transform, T(a,b) itself, or any part thereof. For example, the real part of the wavelet transform, the imaginary part of the wavelet transform, the phase of the wavelet transform, any other suitable part of the wavelet transform, or any combination thereof is intended to be conveyed by the term "scalogram".

A scale, which may be interpreted as a representative temporal period, may be converted to a characteristic frequency of the wavelet function. The characteristic frequency associated with a wavelet of arbitrary a scale is given by

$$f=\frac{f_c}{a} \tag{12}$$

where f_c, the characteristic frequency of the mother wavelet (i.e., at a=1), becomes a scaling constant and f is the representative or characteristic frequency for the wavelet at arbitrary scale a.

Any suitable wavelet function may be used in connection with the present disclosure. One of the most commonly used complex wavelets, the Morlet wavelet, is defined as:

$$\psi(t)=\pi^{-1/4}(e^{i2\pi f_0 t}-e^{-(2\pi f_0)^2/2})e^{-t^2/2} \tag{13}$$

where f_0 is the central frequency of the mother wavelet. The second term in the parenthesis is known as the correction term, as it corrects for the non-zero mean of the complex sinusoid within the Gaussian window. In practice, it becomes negligible for values of $f_0>>0$ and can be ignored, in which case, the Morlet wavelet can be written in a simpler form as

$$\psi(t) = \frac{1}{\pi^{1/4}} e^{i2\pi f_0 t} e^{-t^2/2} \quad (14)$$

This wavelet is a complex wave within a scaled Gaussian envelope. While both definitions of the Morlet wavelet are included herein, the function of equation (14) is not strictly a wavelet as it has a non-zero mean (i.e., the zero frequency term of its corresponding energy spectrum is non-zero). However, it will be recognized by those skilled in the art that equation (14) may be used in practice with $f_0>>0$ with minimal error and is included (as well as other similar near wavelet functions) in the definition of a wavelet herein. A more detailed overview of the underlying wavelet theory, including the definition of a wavelet function, can be found in the general literature. Discussed herein is how wavelet transform features may be extracted from the wavelet decomposition of signals. For example, wavelet decomposition of PPG signals may be used to provide clinically useful information within a medical device.

Pertinent repeating features in a signal give rise to a time-scale band in wavelet space or a resealed wavelet space. For example, the pulse component of a PPG signal produces a dominant band in wavelet space at or around the pulse frequency. FIGS. **3**(*a*) and (*b*) show two views of an illustrative scalogram derived from a PPG signal, according to an embodiment. The figures show an example of the band caused by the pulse component in such a signal. The pulse band is located between the dashed lines in the plot of FIG. **3**(*a*). The band is formed from a series of dominant coalescing features across the scalogram. This can be clearly seen as a raised band across the transform surface in FIG. **3**(*b*) located within the region of scales indicated by the arrow in the plot (corresponding to 60 beats per minute). The maxima of this band with respect to scale is the ridge. The locus of the ridge is shown as a black curve on top of the band in FIG. **3**(*b*). By employing a suitable resealing of the scalogram, such as that given in equation (11), the ridges found in wavelet space may be related to the instantaneous frequency of the signal. In this way, the pulse rate may be obtained from the PPG signal. Instead of resealing the scalogram, a suitable predefined relationship between the scale obtained from the ridge on the wavelet surface and the actual pulse rate may also be used to determine the pulse rate.

By mapping the time-scale coordinates of the pulse ridge onto the wavelet phase information gained through the wavelet transform, individual pulses may be captured. In this way, both times between individual pulses and the timing of components within each pulse may be monitored and used to detect heartbeat anomalies, measure arterial system compliance, or perform any other suitable calculations or diagnostics. Alternative definitions of a ridge may be employed. Alternative relationships between the ridge and the pulse frequency of occurrence may be employed.

As discussed above, pertinent repeating features in the signal give rise to a time-scale band in wavelet space or a resealed wavelet space. For a periodic signal, this band remains at a constant scale in the time-scale plane. For many real signals, especially biological signals, the band may be non-stationary; varying in scale, amplitude, or both over time. FIG. **3**(*c*) shows an illustrative schematic of a wavelet transform of a signal containing two pertinent components leading to two bands in the transform space, according to an embodiment. These bands are labeled band A and band B on the three-dimensional schematic of the wavelet surface. In this embodiment, the band ridge is defined as the locus of the peak values of these bands with respect to scale. For purposes of discussion, it may be assumed that band B contains the signal information of interest. This will be referred to as the "primary band". In addition, it may be assumed that the system from which the signal originates, and from which the transform is subsequently derived, exhibits some form of coupling between the signal components in band A and band B. When noise or other erroneous features are present in the signal with similar spectral characteristics of the features of band B then the information within band B can become ambiguous (i.e., obscured, fragmented or missing). In this case, the ridge of band A may be followed in wavelet space and extracted either as an amplitude signal or a scale signal which will be referred to as the "ridge amplitude perturbation" (RAP) signal and the "ridge scale perturbation" (RSP) signal, respectively. The RAP and RSP signals may be extracted by projecting the ridge onto the time-amplitude or time-scale planes, respectively. The top plots of FIG. **3**(*d*) show a schematic of the RAP and RSP signals associated with ridge A in FIG. **3**(*c*). Below these RAP and RSP signals are schematics of a further wavelet decomposition of these newly derived signals. This secondary wavelet decomposition allows for information in the region of band B in FIG. **3**(*c*) to be made available as band C and band D. The ridges of bands C and D may serve as instantaneous time-scale characteristic measures of the signal components causing bands C and D. This technique, which will be referred to herein as secondary wavelet feature decoupling (SWFD), may allow information concerning the nature of the signal components associated with the underlying physical process causing the primary band B (FIG. **3**(*c*)) to be extracted when band B itself is obscured in the presence of noise or other erroneous signal features.

In some instances, an inverse continuous wavelet transform may be desired, such as when modifications to a scalogram (or modifications to the coefficients of a transformed signal) have been made in order to, for example, remove artifacts. In one embodiment, there is an inverse continuous wavelet transform which allows the original signal to be recovered from its wavelet transform by integrating over all scales and locations, a and b:

$$x(t) = \frac{1}{C_g} \int_{-\infty}^{\infty} \int_{0}^{\infty} T(a,b) \frac{1}{\sqrt{a}} \psi\left(\frac{t-b}{a}\right) \frac{da\,db}{a^2} \quad (15)$$

which may also be written as:

$$x(t) = \frac{1}{C_g} \int_{-\infty}^{\infty} \int_{0}^{\infty} T(a,b) \psi_{a,b}(t) \frac{da\,db}{a^2} \quad (16)$$

where C_g is a scalar value known as the admissibility constant. It is wavelet type dependent and may be calculated from:

$$C_g = \int_0^{\infty} \frac{|\hat{\psi}(f)|^2}{f} df \quad (17)$$

FIG. **3**(*e*) is a flow chart of illustrative steps that may be taken to perform an inverse continuous wavelet transform in accordance with the above discussion. An approximation to the inverse transform may be made by considering equation (15) to be a series of convolutions across scales. It shall be under-

stood that there is no complex conjugate here, unlike for the cross correlations of the forward transform. As well as integrating over all of a and b for each time t, this equation may also take advantage of the convolution theorem which allows the inverse wavelet transform to be executed using a series of multiplications. FIG. **3**(*f*) is a flow chart of illustrative steps that may be taken to perform an approximation of an inverse continuous wavelet transform. It will be understood that any other suitable technique for performing an inverse continuous wavelet transform may be used in accordance with the present disclosure.

FIG. **4** is an illustrative continuous wavelet processing system. In this embodiment, input signal generator **410** generates an input signal **416**. As illustrated, input signal generator **410** may include oximeter **420** coupled to sensor **418**, which may provide as input signal **416**, a PPG signal. It will be understood that input signal generator **410** may include any suitable signal source, signal generating data, signal generating equipment, or any combination thereof to produce signal **416**. Signal **416** may be any suitable signal or signals, such as, for example, biosignals (e.g., electrocardiogram, electroencephalogram, electrogastrogram, electromyogram, heart rate signals, pathological sounds, ultrasound, or any other suitable biosignal), dynamic signals, non-destructive testing signals, condition monitoring signals, fluid signals, geophysical signals, astronomical signals, electrical signals, financial signals including financial indices, sound and speech signals, chemical signals, meteorological signals including climate signals, and/or any other suitable signal, and/or any combination thereof.

In this embodiment, signal **416** may be coupled to processor **412**. Processor **412** may be any suitable software, firmware, and/or hardware, and/or combinations thereof for processing signal **416**. For example, processor **412** may include one or more hardware processors (e.g., integrated circuits), one or more software modules, computer-readable media such as memory, firmware, or any combination thereof. Processor **412** may, for example, be a computer or may be one or more chips (i.e., integrated circuits). Processor **412** may perform the calculations associated with the continuous wavelet transforms of the present disclosure as well as the calculations associated with any suitable interrogations of the transforms. Processor **412** may perform any suitable signal processing of signal **416** to filter signal **416**, such as any suitable band-pass filtering, adaptive filtering, closed-loop filtering, and/or any other suitable filtering, and/or any combination thereof.

Processor **412** may be coupled to one or more memory devices (not shown) or incorporate one or more memory devices such as any suitable volatile memory device (e.g., RAM, registers, etc.), non-volatile memory device (e.g., ROM, EPROM, magnetic storage device, optical storage device, flash memory, etc.), or both. The memory may be used by processor **412** to, for example, store data corresponding to a continuous wavelet transform of input signal **416**, such as data representing a scalogram. In one embodiment, data, representing a scalogram may be stored in RAM or memory internal to processor **412** as any suitable three-dimensional data structure such as a three-dimensional array that represents the scalogram as energy levels in a time-scale plane. Any other suitable data structure may be used to store data representing a scalogram.

Processor **412** may be coupled to output **414**. Output **414** may be any suitable output device such as, for example, one or more medical devices (e.g., a medical monitor that displays various physiological parameters, a medical alarm, or any other suitable medical device that either displays physiological parameters or uses the output of processor **412** as an input), one or more display devices (e.g., monitor, PDA, mobile phone, any other suitable display device, or any combination thereof), one or more audio devices, one or more memory devices (e.g., hard disk drive, flash memory, RAM, optical disk, any other suitable memory device, or any combination thereof), one or more printing devices, any other suitable output device, or any combination thereof.

It will be understood that system **400** may be incorporated into system **10** (FIGS. **1** and **2**) in which, for example, input signal generator **410** may be implemented as parts of sensor **12** and monitor **14** and processor **412** may be implemented as part of monitor **14**.

The processing system may identify a change in a feature of the pulse rhythm of patient blood at the measurement site (e.g., the location on the patient's body associated with sensor **12**). For example, the processing system may identify morphology changes, and corresponding pulse rhythm abnormalities may be detected in signals such as PPG signals. A pulse rhythm is the rhythmical throbbing of arteries produced by the regular contractions of the heart and may differ from a patient's heart rate, as a result of the patient's blood pressure, vasoconstriction, vasodilation, or other physiological attributes. With reference to the present context, a pulse rhythm abnormality may arise from an irregular firing of the heart that results in an identifiable morphology in the physiological signal, in a transformation of the signal such as a wavelet transformation, or both.

FIG. **5** shows PPG signal **500** that may be analyzed in accordance with the present disclosure. PPG signal **500** is an oscillating signal having pulses such as pulses **502**. Each pulse of PPG signal **500** may correspond to a cardiac cycle. PPG signal **500** has AC component **504**, which oscillates around baseline **540**. For example, as shown in FIG. **5**, during the time periods corresponding to different pulses or sets of pulses, PPG signal **500** may be oscillating around different baselines (e.g., baseline **540** during time period **506**, baseline **542** during time period **508**). The baseline of signal **500** may be calculated using any suitable technique. For example, the baseline may be calculated as an average of signal **500** over a selected amount of time or over a selected number of cardiac cycles.

In some embodiments, a signal processing system, such as signal processing system **400** of FIG. **4**, receives PPG signal **500**, and identifies one or more of local minimum point **510**, local maximum point **512**, local minimum point **520**, and local maximum point **522** in the PPG signal **500**. The signal processing system may pair each local minimum point with an adjacent maximum point. For example, the signal processing system may pair points **510** and **512** to identify one segment, points **512** and **520** to identify a second segment, points **520** and **522** to identify a third segment and points **522** and **530** to identify a fourth segment. The slope of each segment is measured to determine whether the segment corresponds to an upstroke portion of the pulse (e.g., a positive slope) or a downstroke portion of the pulse (e.g., a negative slope) portion of the pulse. A pulse may be defined as a combination of at least one upstroke and one downstroke. For example, the segment identified by points **510** and **512** and the segment identified by points **512** and **520** may define a pulse. In another example, the segments identified by points **510** and **530** may define a pulse.

In some embodiments, PPG signal **500** includes a dichrotic notch **550** or other notches (not shown) in different sections of the pulse (e.g., at the beginning (referred to as an ankle notch), in the middle (referred to as a dichrotic notch), or near the top (referred to as a shoulder notch). The signal processing sys-

tem may identify notches and either utilize or ignore them when detecting the pulse locations. In some embodiments, the signal processing system computes the second derivative of the PPG signal to find the local minima and maxima points and uses this information to determine a location of, for example, a dichrotic notch. Additionally, the signal processing system may interpolate between points in signal **500** or between points in a processed signal using any interpolation technique (e.g., zero-order hold, linear interpolation, higher-order interpolation techniques). Some pulse detection techniques that may be performed by the signal processing system are described in more detail in co-pending, commonly assigned U.S. patent application Ser. No. 12/242,908, filed Sep. 30, 2008 and entitled "SYSTEMS AND METHODS FOR DETECTING PULSES IN A PPG SIGNAL," which is incorporated by reference herein in its entirety.

AC component **504** may be caused in part by a change in blood volume at a sensor location. The change in blood volume may be caused by the pressure wave generated by each heartbeat. The size of AC component **504** may correspond to the change in blood pressure at the sensor location (e.g., the difference between systolic and diastolic pressure in the arteries). As shown in FIG. **5**, the amplitude of AC component **504** is higher during time period **506** than during time period **508**. In addition to the AC component, PPG signal **500** also has amplitude component **514**, which may be attributed to the total amount of absorption and/or transmission between the sensor emitter and detector. As shown in FIG. **5**, amplitude component **514** also changes between time period **506** ("zero" amplitude) and time period **508**.

In some embodiments, the signal processing system analyzes PPG signal **500** to calculate signal characteristics. The calculated signal characteristic may be any suitable characteristic such as an average or median amplitude of the AC component over a selected amount of time or over a selected number of cardiac events. For example, the signal processing system analyzes PPG signal **500** to calculate the length, amplitude, or both of a single downstroke portion of a pulse and an average value (e.g., mean, median) of the length, amplitude, or both of the downstroke portions of pulses over a selected amount of time or over a selected number of cardiac cycles. In other examples, the signal processing system analyzes PPG signal **500** to calculate the period of a single pulse and an average value (e.g., mean, median) of the period of pulses over a selected amount of time or over a selected number of cardiac cycles. In another example, the signal processing system may analyze PPG signal **500** to calculate the area of a single pulse and an average value (e.g., mean, median) of the area of pulses over a selected amount of time or over a selected number of cardiac cycles. It will be understood that the signal processing system may use any other suitable algorithm to calculate the desired signal characteristic.

The signal processing system may detect a pulse rhythm abnormality at a measurement site by calculating signal characteristics of PPG signal **500** and detecting changes in the signal morphology and characteristics. In some embodiments, the signal processing system characterizes one or more of the amplitude, timing, period, morphology, or other suitable characteristics of PPG signal **500** to detect a pulse rhythm abnormality. For example, the signal processing system may detect irregular pulses by comparing the length or the amplitude of a downstroke against a mean or median value. When the length of the amplitude of an individual downstroke exceeds a threshold value (e.g., 1.8 times the median value, or any other predetermined or calculated value), the downstroke may be identified as corresponding to an abnormal pulse. In another example, the signal processing system may detect abnormal pulses by comparing the period of a pulse against a mean or median value. When the period of an individual pulse exceeds a threshold value (e.g., 1.8 times the median value), the pulse may be identified as corresponding to an abnormal pulse. The signal processing system may also detect abnormal pulses by comparing the area of a pulse against a running mean or median value.

The signal processing system may monitor one or more signal characteristics to detect that a pulse rhythm abnormality has occurred. For example, as shown in FIG. **5**, the length of a downstroke portion (e.g., from local maximum **512** to local minimum **520**), the period of a pulse (e.g., the period corresponding to time period **506**), or both may change to a different length (e.g., from local maximum **532** to local minimum **552**), a different period (e.g., the period corresponding to time period **508**), or both. The signal processing system may analyze these changes and determine that a pulse rhythm abnormality has occurred. For example, the signal processing system may detect that the patient has experienced an arrhythmia.

It will be understood that although a PPG signal as described above is suitable to detect events, other signals or devices may be used to detect events such as, for example, an electrocardiogram (ECG), electroencephalogram (EEG), electrogastrogram (EGG), electromyogram (EMG), heart rate signals, pathological sounds, ultrasound, or any other suitable biosignal, dynamic signals, non-destructive testing signals, condition monitoring signals, fluid signals, geophysical signals, astronomical signals, electrical signals, financial signals including financial indices, sound and speech signals, chemical signals, meteorological signals including climate signals, any other suitable signals, or any combination thereof.

In some embodiments, the signal processing system may also detect an event by transforming a received signal. For example, the signal processing system may detect pulse rhythm abnormalities from within PPG signals by monitoring morphology changes in the PPG signal, analyzing a transformation of the PPG signal such as a wavelet transformation using a continuous wavelet transform, or using a combination of the signal and a transformed signal or signals. In some embodiments, the PPG signal may be differentiated before being processed, transformed, or both to better resolve the signal characteristics.

The detection of a pulse rhythm abnormality may be used to determine physiological information indicative of cardiac arrhythmia. For example, the signal processing system may identify or diagnose arrhythmias and heartbeat irregularities in the patient such as, for example, atrial flutter, atrial fibrillation, sinus tachycardia, ventricular tachycardia, ventricular fibrillation, bradycardia, bigeminy, trigeminy, an isolated irregularity such as an ectopic beat, any other suitable physiological information, or any combination thereof based on the pulse rhythm abnormality information. Illustrative pulse rhythm abnormalities are shown in FIGS. **6-9** in accordance with some embodiments of the present disclosure.

FIG. **6** illustrates a pulse rhythm abnormality in the form of an isolated irregularity, referred to as an ectopic. In particular, FIG. **6** shows amplitude-time plot **602** of an ECG signal **604**, amplitude-time plot **612** of a PPG signal **614** taken at the same time as ECG signal **604**, and scale-time-amplitude plot **622** of scalogram **624** generated from a continuous wavelet transform of PPG signal **614** in accordance with some embodiments. Scalogram **624** includes pulse band **626**, calculation region **630**, and isolated irregularity time period **640**. Normal pulse rhythm occurs in the region before isolated irregularity

time period **640** and resumes after isolated irregularity time period **640**. Time is represented by the horizontal axes of plots **602**, **612**, and **622** while amplitude is represented by the vertical axes of plots **602** and **612** and the shading of plot **622** and scale is represented by the vertical axis of plot **622**.

The signal processing system may use various metrics to detect the ectopic (and any other pulse rhythm abnormalities) within PPG signal **614**, scalogram **624**, or both. In some embodiments, the signal processing system characterizes the amplitude, timing, period, morphology, any other suitable characteristic, or any combination thereof of a pulse or pulses of PPG signal **614**. In some embodiments, the signal processing system characterizes the morphology of localized energy increases below pulse band **626** and localized energy decreases on pulse band **626** of scalogram **624**.

The signal processing system may calculate any suitable energy parameter within a region on the scalogram (e.g., region **630**). The size and shape (e.g., horizontal and vertical ranges, aspect ratio) of region **630** may be selected in any suitable way. For example, the vertical range and location of region **630** may be selected to cover the pulse band **626**. Pulse band **626** may vary its location and size over time. Therefore, in an embodiment, region **630** may be centered over the ridge of pulse band **626**. The ridge of pulse band **626** may be identified, for example, using ridge following techniques or any other suitable technique such as using heart rate calculated from PPG signal **614**. The ridge of the pulse band may be identified, for example, using the techniques described in Watson et al., U.S. patent application Ser. No. 12/245,326, filed Sep. 30, 2008, entitled "SYSTEMS AND METHODS FOR RIDGE SELECTION IN SCALOGRAMS OF SIGNALS," which is incorporated by reference herein in its entirety. With the ridge location known, the vertical range of region **630** may be selected to span a selected number of scales above and below the ridge. The number of scales may be selected such that region **630** spans only a portion of pulse band **626**, all of pulse band **626**, or all of pulse band **626** plus an additional amount. The vertical range and location of region **630** may be fixed to cover the range of scales where the pulse band is expected to be located based on historical heartbeat or pulse rhythm data for a certain patient or a certain patient type. For example, the vertical range of region **630** may span from a scale whose characteristic frequency is about 0.5 Hz to a scale whose characteristic frequency is about 4 Hz or equivalently 30-240 bpm. The horizontal range of region **630** may be selected to cover any suitable length of time, such as 1, 2, 3, 4, 5, etc. seconds. Region **630** may slide across the scalogram calculating the energy parameter in real-time or off-line. The energy parameter calculated within region **630** may be, for example, the average or median energy within the region.

The signal processing system may identify a morphology change and detect a pulse rhythm abnormality by comparing one or more parameters calculated within region **630** against an average value, such as a mean or median value, or any other suitable reference. In some embodiments, the signal processing system may identify a morphology change and detect a pulse rhythm abnormality when region **630**, which may be progressing in time, reaches the region corresponding to region **640**. For example, the signal processing system may detect a pattern of regular pulses **632**. The signal processing system may detect a pulse rhythm abnormality in the form of isolated irregularity **646** (e.g., corresponding to an ectopic beat) by, for example, identifying a change in the pattern of regular pulses beginning at time **642**, when the pattern of regular pulses ends, and ending at time **644**, when the pattern of regular pulses resumes.

In the example of FIG. **6**, the patient exhibits an isolated irregularity in region **640**. Region **640** has a distinct morphology in scalogram **624** (as shown by the arrow pointing to region **646**). The morphology of region **640** is distinct from normal because pulse band **626** breaks up and localized regions of higher energy **646** appear at lower scales (resulting in downshifting of energy to lower frequencies). The signal processing system may characterize the morphology change of localized energy increases below pulse band **626** and localized energy decreases on pulse band **626** and identify a pulse rhythm abnormality based on, for example, the morphology change. Thus, by analyzing particular morphology changes and characteristics in various regions of scalogram **624**, pulse rhythm abnormalities may be detected. For example, the signal processing system may analyze the real part, imaginary part, phase, or any combination thereof of the morphology in the various regions. As another example, the signal processing system may analyze characteristics such as energy parameters in the various regions. It will be understood that any other suitable energy parameter may also be used. The signal processing system may also calculate percentage or magnitude changes in the energy parameter over time. In an embodiment, the amplitude of the ridge of the pulse band may be analyzed in place of or in addition to the energy of the pulse band.

In some embodiments, the signal processing system may detect the occurrence of a pulse rhythm abnormality using either the calculated energy parameters or the detected morphology change. For example, based at least in part on a portion of wavelet transform **624** (e.g., a portion of region **630**), the signal processing system may calculate or use one or more predetermined thresholds. If the calculated energy parameter or detected artifact exceeds a threshold, the signal processing system may determine that a pulse rhythm abnormality has occurred.

In some embodiments, PPG signal **614** and scalogram **624** are used together to detect pulse rhythm abnormalities. For example, the signal processing system detects the pulse rhythm abnormality by analyzing features of both the PPG and its corresponding scalogram. As another example, the signal processing system may detect the pulse rhythm abnormality by utilizing portions of PPG signal **614** and wavelet transform **624**. For instance, the signal processing system may determine when a pulse rhythm abnormality occurs in scalogram **624** (e.g., during the time period corresponding to region **640**). Based at least in part on this information, the signal processing system may compare signal characteristics of PPG signal **614** in the time period before the pulse rhythm abnormality and with signal characteristics of PPG signal **614** after the pulse rhythm abnormality. Furthermore, the signal processing system may determine when the morphology change occurs in PPG signal **614**. Based at least in part on this information, the signal processing system may calculate changes in the characteristics (e.g., energy parameters) of wavelet transform **624** in the time period before the morphology change and after the morphology change.

FIG. **7** illustrates a pulse rhythm abnormality in the form of a repetitive irregularity, known as bigeminy. In particular, FIG. **7** shows amplitude-time plot **712** of a PPG signal **714** and scale-time-amplitude plot **722** of scalogram **724** generated from a continuous wavelet transform of PPG signal **714**. Time is represented by the horizontal axes of plots **712** and **722**, amplitude is represented by the vertical axis of plot **712** and the shading of plot **722**, and scale is represented by the vertical axis of plot **722**.

PPG signal **714** is acquired from a patient exhibiting bigeminy. Bigeminy is characterized by an abnormal heartbeats

occurring every other concurrent beat. Bigeminy can be detected in scalogram **724** because of a pattern of consecutive normal-abnormal-normal local amplitude (or, energy) minimums occurring at scales (or frequencies) greater than the pulse band, as seen for example in the pattern illustrated by consecutive points **732**, **736**, and **734**. The signal processing system may use various metrics to detect bigeminy from PPG signal **714**, scalogram **724**, or both. In some embodiments, the signal processing system characterizes the amplitude, timing, period, morphology, pattern, any other suitable characteristic, or any combination thereof of a pulse or pulses of PPG signal **714**, scalogram **724**, or both.

In some embodiments, the signal processing system may characterize one or more of the morphology of scalogram **724**, the characteristic pulse groupings of two in wavelet space (as shown in region **730**, which may be progressing in time as described with reference to region **630** shown in FIG. **6**), or any combination thereof. For example, the signal processing system may identify normal pulse **732** followed by abnormal pulse **736** and normal pulse **734**. The signal processing system may determine that this pattern (i.e., every other pulse being abnormal) is indicative of bigeminy by calculating the amplitude values as a function of time for each scale included in region **730** and comparing the local maximum and minimum points to identify a pattern of a local minimum, as seen, for example, in the local minimum corresponding to normal pulse **734**, followed by a higher amplitude local minimum such as local minimum corresponding to abnormal pulse **736**.

In some embodiments, bigeminy is detected by monitoring PPG signal **714**, a transformation of PPG signal **714** such as wavelet transformation **724**, or both. Thus, by analyzing particular morphology changes and characteristics in various regions of scalogram **724**, bigeminy may be detected. For example, the signal processing system may analyze the real part, imaginary part, phase, any other component, or any combination thereof of the morphology in the various regions, which are not shown in FIG. **7** to avoid overcomplicating the figure. As another example, the signal processing system may analyze characteristics such as energy parameters in the various regions.

FIG. **8** illustrates a pulse rhythm abnormality in the form of a repetitive irregularity, known as trigeminy. In particular, FIG. **8** shows amplitude-time plot **812** of a PPG signal **814** and scale-time-amplitude plot **822** of scalogram **824** generated from a continuous wavelet transform of PPG signal **814**. Time is represented by the horizontal axes of plots **812** and **822**, amplitude is represented by the vertical axis of plot **812** and the shading of plot **822**, and scale is represented by the vertical axis of plot **822**.

PPG signal **814** is acquired from a patient exhibiting trigeminy. Trigeminy is characterized by abnormal heartbeats occurring at intervals of two normal beats to one abnormal heartbeat. Trigeminy can be detected in scalogram **824** because of a pattern of consecutive normal-abnormal-abnormal-normal local amplitude (or energy) minimums occurring at scales (i.e., frequencies) greater than the pulse band, as seen for example in the pattern illustrated by consecutive points **832**, **836** (two in number), and **834**. The signal processing system may use various metrics to detect trigeminy from PPG signal **814**, scalogram **824**, or both. In some embodiments, the signal processing system characterizes the amplitude, timing, period, morphology, pattern, any other suitable characteristic, or any combination thereof of a pulse or pulses of PPG signal **814**, scalogram **824**, or both.

In some embodiments, the signal processing system may characterize one or more of the morphology of scalogram **824**, the characteristic pulse groupings of three in wavelet space (as shown in region **830**, which may be progressing in time as described with reference to region **630** shown in FIG. **6**), or any combination thereof. For example, the signal processing system may identify normal pulse **832** followed by abnormal pulses **836** and normal pulse **834**. The signal processing system may determine that this pattern (i.e., every third pulse being abnormal) is indicative of trigeminy by calculating the amplitude values as a function of time for each scale included in region **830** and comparing the local maximum and minimum points to identify a pattern of a local minimum (e.g., local minimum corresponding to normal pulse **834**) followed by two higher amplitude local minimums (e.g., local minimums corresponding to abnormal pulses **836**).

In some embodiments, trigeminy is detected by monitoring PPG signal **814**, a transformation of PPG signal **814** such as wavelet transformation **824**, or both. Thus, by analyzing particular morphology changes and characteristics in various regions of scalogram **824**, trigeminy may be detected. For example, the signal processing system may analyze the real part, imaginary part, phase, any other suitable component, or any combination thereof of the morphology in the various regions, which are not shown in FIG. **8** to avoid overcomplicating the figure. As another example, the signal processing system may analyze characteristics such as energy parameters in the various regions.

FIG. **9** illustrates a pulse rhythm abnormality indicative of extensive atrial fibrillation. As shown, the scalogram is nearly void of any regularities. In particular, FIG. **9** shows amplitude-time plot **912** of a PPG signal **914** and scale-time-amplitude plot **922** of scalogram **924** generated from a continuous wavelet transform of PPG signal **914**. Time is represented by the horizontal axes of plots **912** and **922**, amplitude is represented by the vertical axis of plot **912** and the shading of plot **922**, and scale is represented by the vertical axis of plot **922**.

PPG signal **914** is acquired from a patient exhibiting atrial fibrillation. Atrial fibrillation is characterized by erratic heart QRS intervals and manifests itself in PPG signal **914** as erratically varying amplitudes and periods of the pulses. Atrial fibrillation can be detected in scalogram **924** by the absence of a pulse band and the absence of a pattern of local minimum and maximum points at scales (i.e., frequencies) above an expected pulse band based on historical heartbeat or pulse rhythm data for a certain patient or patient type. The signal processing system may use various metrics to detect atrial fibrillation from PPG signal **914**, scalogram **924**, or both. In some embodiments, the signal processing system may characterize the amplitude, timing, period, morphology, or any combination thereof of a pulse, pulses, or absence thereof of PPG signal **914**, scalogram **924**, or both.

In some embodiments, the signal processing system may characterize the morphology, the erratic energy distribution within the vicinity of the pulse band of scalogram **924** (as shown in region **930**, which may be progressing in time as described with reference to region **630** shown in FIG. **6**), any other suitable characteristic, or any combination thereof. For example, the signal processing system may identify the absence of normal pulses in region **930**. In another example, the signal processing system may identify the absence of a pulse band in scalogram **924**, region **930**, or both. The signal processing system may determine that this pattern (i.e., no normal pulse pattern) is indicative of atrial fibrillation.

In some embodiments, atrial fibrillation is detected by monitoring PPG signal **914**, a transformation of PPG signal **914** such as wavelet transformation **924**, or both. Thus, by

analyzing particular morphology changes and characteristics in various regions of scalogram **924**, atrial fibrillation may be detected. For example, the signal processing system may analyze the real part, imaginary part, phase, or any combination thereof of the morphology in the various regions. As another example, the signal processing system may analyze characteristics such as energy parameters in the various regions.

FIG. **10** is a flow diagram **1000** of illustrative steps involved in determining cardiac arrhythmia based on an identified pulse rhythm abnormality in a transformation of a monitored PPG signal. The steps of flow diagram **1000** may be performed by processor **412** or may be performed by any suitable processing device communicatively coupled to monitor **14** (FIGS. **1** and **2**). It will be noted that the steps of flow diagram **1400** may be performed in any suitable order, and one or more steps may be omitted entirely according to the context and application.

At step **1002**, a signal (e.g., signal **416** shown in FIG. **4**) is received from a patient (e.g., patient **40** of FIG. **2**). The received signal may be generated by sensor unit **12** (FIGS. **1-2**), which may include any of the physiological sensors described herein, or any other sensor. A received signal may be signal **416**, generated by pre-processor **420** coupled between processor **412** and sensor **418** (FIG. **4**). A received signal may include multiple signals, for example, in the form of a multi-dimensional vector signal or a frequency-multiplexed or time-multiplexed signal. In certain embodiments, the signal received at step **1002** includes a PPG signal, such as PPG signal **500** of FIG. **5**, PPG signal **614** of FIG. **6**, PPG signal **714** of FIG. **7**, PPG signal **814** of FIG. **8**, PPG signal **914** of FIG. **9**, or any other suitable signal.

At step **1004**, a transformed signal is generated from the signal received at step **1002**. The processing at step **1004** may include transforming a signal into another domain, such as a Fourier, wavelet, spectral, scale, time, time-spectral, time-scale domain, or any transform space using, for example, processor **412**. For example, a scalogram (e.g., scalogram **624** shown in FIG. **6**, scalogram **724** shown in FIG. **7**, scalogram **824** shown in FIG. **8**, scalogram **924** shown in FIG. **9**) may be generated by performing a wavelet transformation of a received PPG signal using a processor (e.g., processor **412** shown in FIG. **4**). The wavelet transform may, for example, be a continuous or discrete wavelet transform. A transformation may include a continuous wavelet transformation as described, for example, in Paul S. Addison, The Illustrated Wavelet Transform Handbook (Taylor & Francis Group 2002).

Any of the operations described herein may be applied to a portion or portions of a received signal. An operation may be broken into one or more stages, performed by one or more devices, or both within signal processing system **400** of FIG. **4** (which may itself be a part of patient monitoring system **10** of FIGS. **1** and **2**). In some embodiments, a filtering technique is applied by input signal generator **410** (FIG. **4**) prior to passing the resulting input signal **416** (FIG. **4**) to processor **412**, where it may undergo a transformation. For example, step **1004** may include filtering a signal, such as signal **416** (FIG. **4**), mathematically manipulating a signal, convolving a signal with a reference signal, or any combination thereof.

At step **1006**, the signal processing system detects a change in a feature of the transformed signal. In some embodiments, the signal processing system calculates characteristics of the scalogram such as an energy parameter, morphology, pattern, or any combination thereof within a region (e.g., region **630** of FIG. **6**, region **730** of FIG. **7**, region **830** of FIG. **8**, region **930** of FIG. **9**) of the scalogram. The size and shape of the region may be selected in any suitable way. For example, the height and location of the region may be fixed or may be dynamically changed to cover a band or region of interest in the scalogram.

At step **1008**, the signal processing system identifies a pulse rhythm abnormality based on the detected change in the feature of the transformed signal. For example, the signal processing system may determine that a detected pattern of normal pulses (e.g., normal pulses **632** shown in FIG. **6**) followed by an abnormal pulse (e.g., abnormal pulse **646**) is indicative of an occasional or isolated irregularity such as an ectopic beat. In another example, the signal processing system may determine that a detected pattern of a normal pulse (e.g., normal pulse **732** shown in FIG. **7**) followed by an abnormal pulse (e.g., abnormal pulse **736**) is indicative of bigeminy (i.e., every other pulse being abnormal). In another example, the signal processing system may determine that a detected pattern of a normal pulse (e.g., normal pulse **832** shown in FIG. **8**) followed by two abnormal pulses (e.g., abnormal pulses **836**) is indicative of trigeminy (i.e., every third pulse being abnormal). In another example, the signal processing system may determine that an absence of normal pulses (e.g., region **930** shown in FIG. **9**) is indicative of atrial fibrillation.

At step **1010**, the signal processing system analyzes the detected change in the feature of the transformed signal, identified pulse rhythm abnormality, or both to identify one or more irregularities in the scalogram patterns, which can be used to determine physiological information, such as cardiac arrhythmia. For example, the detection of a pulse rhythm abnormality may be used to identify or diagnose arrhythmias and heartbeat irregularities in the patient such as, for example, atrial flutter, atrial fibrillation, sinus tachycardia, ventricular tachycardia, ventricular fibrillation, bradycardia, bigeminy, trigeminy, an isolated irregularity such as an ectopic beat, any other suitable physiological information, or any combination thereof based on the pulse rhythm abnormality information.

The signal processing system may also determine cardiac arrhythmia by analyzing an original signal and the transform of that signal. For example, the signal processing system may determine when a change in a feature of the transformed signal occurs. Based at least in part on this information, the signal processing system may analyze changes in the signal characteristics of the original signal before and after the occurrence of the detected change in the transformed signal to determine whether a pulse rhythm abnormality occurs. For example, the signal characteristics of the original signal prior to the occurrence of the detected change may be compared to the signal characteristics of the original signal after the occurrence of the artifact.

In some embodiments, the detection of a pulse rhythm abnormality may also cause an action to be performed (e.g., as an optional step of flow diagram **1000**). For example, processor **416** (FIG. **4**) may provide a flag that indicates that further analysis needs to be performed. In another example, processor **416** may output an indication of arrhythmia or an indication of the specific arrhythmia type to display **20** (FIG. **1**), display **28** (FIG. **1**), any other suitable component (e.g., via output **414** shown in FIG. **4**), or any combination thereof in response to the detection of a pulse rhythm abnormality. In other implementations, processor **416** may provide an audible alarm, visual alarm, any other suitable alarm, or any combination thereof to output **414**, monitor **14**, monitor **26**, any other suitable component, or any combination thereof in response to the detection of a pulse rhythm abnormality (e.g., associated with an arrhythmia). In some embodiments, respiratory rate, pulse rate, any other suitable physiological

information, or any combination thereof may be displayed (e.g., on display **20**, display **28**, or both shown in FIG. **1**) together with the arrhythmia information. In some embodiments, arrhythmia information may replace physiological information displayed on a display screen.

It will be understood that the foregoing is only illustrative of the principles of the disclosure, and that the disclosure can be practiced by other than the described embodiments, which are presented for purposes of illustration and not of limitation. Variations and modifications will occur to those of skill in the art after reviewing this disclosure. The disclosed features may be implemented, in any combination and subcombinations (including multiple dependent combinations and sub-combinations), with one or more other features described herein. The various features described or illustrated above, including any components thereof, may be combined or integrated in other systems. Moreover, certain features may be omitted or not implemented. Examples of changes, substitutions, and alterations are ascertainable by one skilled in the art and could be made without departing from the scope of the information disclosed herein.

What is claimed is:

1. A method for determining cardiac arrhythmia in a patient comprising:

electronically receiving a photoplethysmograph signal of a subject from a sensing device, wherein the photoplethysmograph signal comprises a plurality of downstroke regions;

calculating a measure of a first downstroke region;

calculating an average measure of two or more downstroke regions;

comparing the measure of the first downstroke region and the average measure;

detecting a change in a feature of the signal based at least in part on the comparison;

generating a transformed signal based at least in part on a transformation of the photoplethysmograph signal;

detecting a change in a feature of the transformed signal;

identifying information indicative of a pulse rhythm abnormality based at least in part on the detected change in the feature of the transformed signal; and

determining cardiac arrhythmia in the subject based at least in part on the information indicative of the pulse rhythm abnormality and the detected change in the feature of the photoplethysmograph signal.

2. The method of claim **1**, wherein the detecting the change in the feature of the transformed signal comprises detecting a change in the feature of the transformed signal based at least in part on a comparison of the feature of the transformed signal and a threshold value.

3. The method of claim **1**, wherein the cardiac arrhythmia comprises one of bigeminy, trigeminy, and a combination thereof.

4. The method of claim **1**, further comprising providing for display an indication of cardiac arrhythmia based at least in part on the determined cardiac arrhythmia.

5. A system for determining physiological information about a subject, the system comprising:

a signal input configured to receive a photoplethysmograph signal of a subject from a sensing device; and

electronic processing equipment coupled to the signal input, the electronic processing equipment configured to:

receive the photoplethysmograph signal;

generate a scalogram based at least in part on a wavelet transformation of the photoplethysmograph signal, wherein the scalogram comprises a pulse band region, a region of scales greater than the pulse band region, and a region of scales lower than the pulse band region;

determine a parameter indicative of energy distribution of the scalogram for a time interval;

compare the parameter indicative of energy distribution of the scalogram for the time interval against a reference energy parameter value, wherein the reference energy parameter value comprises an average measure of the energy parameter indicative of distribution of the scalogram for two or more time intervals;

detect a pattern of changes in an energy distribution of one or more of the pulse band region, the region of scales greater than the pulse band region, and the region of scales lower than the pulse band region based at least in part on the comparison;

identify information indicative of a pulse rhythm abnormality based at least in part on the detected pattern of changes, wherein the pulse rhythm abnormality comprises a repetitive irregularity indicated by a pattern of normal and abnormal pulse characteristics; and

determine cardiac arrhythmia in the subject based at least in part on the information indicative of the pulse rhythm abnormality.

6. The system of claim **5**, wherein the photoplethysmograph signal comprises a plurality of pulse regions, and wherein the electronic processing equipment is further configured to:

calculate a measure of the period of a first pulse region;

calculate an average measure of the periods of two or more pulse regions;

compare the measure of the period of the first pulse region and the average measure of the periods; and

detect a pattern of changes in a feature of the signal based at least in part on the comparison of the measure of the period of the first pulse region and the average measure of the periods.

7. The system of claim **5**, wherein the photoplethysmograph signal comprises a plurality of pulse regions, and wherein the electronic processing equipment is further configured to:

calculate a measure of the area of a first pulse region;

calculate an average measure of the areas of two or more pulse regions;

compare the measure of the area of the first pulse region and the average measure of the areas; and

detect a pattern of changes in a feature of the signal based at least in part on the comparison of the measure of the area of the first pulse region and the average measure of the areas.

8. The system of claim **5**, wherein the cardiac arrhythmia comprises one of bigeminy, trigeminy, and a combination thereof.

9. The system of claim **5**, wherein the electronic processing equipment is further configured to provide for display an indication of cardiac arrhythmia based at least in part on the determined cardiac arrhythmia.

10. A system for determining physiological information about a subject, the system comprising:

a signal input configured to receive a photoplethysmograph signal of a subject from a sensing device, wherein the photoplethysmograph signal comprises a plurality of downstroke regions; and

electronic processing equipment coupled to the signal input, the electronic processing equipment configured to:

receive the photoplethysmograph signal;

calculate a measure of a first downstroke region;

calculate an average measure of two or more downstroke regions;

compare the measure of the first downstroke region and the average measure;

detect a pattern of changes in a feature of the signal based at least in part on the comparison;

generate a scalogram based at least in part on a wavelet transformation of the photoplethysmograph signal, wherein the scalogram comprises a pulse band region, a region of scales greater than the pulse band region, and a region of scales lower than the pulse band region;

determine a parameter indicative of energy distribution of the scalogram for a time interval;

compare the parameter indicative of energy distribution of the scalogram for the time interval against a reference energy parameter value;

detect a pattern of changes in an energy distribution of one or more of the pulse band region, the region of scales greater than the pulse band region, and the region of scales lower than the pulse band region based at least in part on the comparison;

identify information indicative of a pulse rhythm abnormality based at least in part on the detected patterns of changes, wherein the pulse rhythm abnormality comprises a repetitive irregularity indicated by a pattern of normal and abnormal pulse characteristics; and

determine cardiac arrhythmia in the subject based at least in part on the information indicative of the pulse rhythm abnormality.

11. The system of claim **10**, wherein the reference energy parameter value comprises a threshold value.

12. The system of claim **10**, wherein the cardiac arrhythmia comprises one of bigeminy, trigeminy, and a combination thereof.

13. The system of claim **10**, wherein the electronic processing equipment is further configured to provide for display an indication of cardiac arrhythmia based at least in part on the determined cardiac arrhythmia.

14. A non-transitory computer-readable medium for use in determining cardiac arrhythmia in a patient, the computer-readable medium having computer program instructions recorded thereon for:

electronically receiving a photoplethysmograph signal of a subject from a sensing device, wherein the photoplethysmograph signal comprises a plurality of downstroke regions;

calculating a measure of a first downstroke region;

calculating an average measure of two or more downstroke regions;

comparing the measure of the first downstroke region and the average measure;

detecting a change in a feature of the signal based at least in part on the comparison;

generating a transformed signal based at least in part on a transformation of the photoplethysmograph signal;

detecting a change in a feature of the transformed signal;

identifying information indicative of a pulse rhythm abnormality based at least in part on the detected change in the feature of the transformed signal; and

determining cardiac arrhythmia in the subject based at least in part on the information indicative of the pulse rhythm abnormality.

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